The Nature and Role of Prototyping in Weapon System Development

Jeffrey A. Drezner

RAND | NATIONAL DEFENSE RESEARCH INSTITUTE

The research described in this report was sponsored by the Under Secretary of Defense for Acquisition. The research was conducted in the National Defense Research Institute, RAND's federally funded research and development center supported by the Office of the Secretary of Defense and the Joint Chiefs of Staff, Contract No. MDA903-90-C-0040.

Library of Congress Cataloging in Publication Data

Drezner, Jeffrey A.
The nature and role of prototyping in weapon system development / Jeffrey A. Drezner.
p. cm
"Prepared for the Office of the Under Secretary of Defense (Acquisition)."
"R-4161-ACQ."
Includes bibliographical references.
ISBN 0-8330-1228-2
1. Weapons systems—Design and construction. 2. United States—Armed Forces—Weapons systems—Design and construction.
3. Prototypes, Engineering. I. United States Office of the Under Secretary of Defense, Acquisition. II. Title.
UF500.D74 1992
355.8'2—dc20 92-7676
CIP

Published 1992 by RAND
1700 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138

R-4161-ACQ

The Nature and Role of Prototyping in Weapon System Development

Jeffrey A. Drezner

Prepared for the
Under Secretary of Defense for Acquisition

RAND

PREFACE

RAND has undertaken a research effort focused on identifying and analyzing the range of system and subsystem prototyping strategies available to the Department of Defense (DoD) and appropriate to the acquisition environment of the late 1980s and 1990s. As part of that effort, this report examines the general nature of prototyping, develops an analytical framework for thinking about prototyping in weapon system development, and analyzes past and present prototyping programs within this framework.

This report should be of interest to officials and analysts both inside and outside the government concerned with improving the efficiency of the weapons acquisition process.

This work was sponsored by the Under Secretary of Defense for Acquisition. It was carried out in the Acquisition and Support Policy Program and was performed under the auspices of RAND's National Defense Research Institute, a federally funded research and development center supported by the Office of the Secretary of Defense and the Joint Staff.

SUMMARY

Confusion regarding terms has historically led to inconsistencies in acquisition policy and strategies. One such term, prototyping, has been used in many different ways, and many different prototyping strategies have been applied to weapon system development programs. Thus, despite numerous attempts to define optional prototyping policies, there is little consensus on when, or with what objectives, prototypes should be used.

This research is an attempt to alleviate that problem by exploring the nature and role of prototyping in weapon system development. The issue is of growing concern because of increased interest expressed by Congress (and institutionalized in Department of Defense [DoD] acquisition regulations) and also because of the changing acquisition environment (declining budgets, fewer new program starts, and increasing system complexity). Our objectives are to:

- Improve understanding of the fundamental nature and role of prototyping as an acquisition strategy in weapon system development.
- Examine the most common prototyping strategies and how they have changed over time.
- Investigate the relationship between prototyping and program outcomes.
- Make recommendations on what kind of policy, if any, DoD should have regarding the use of prototyping in weapon system development.

We address these issues by adopting a large sample empirical research approach. Two databases were developed to support the analysis: a literature review that included information on 287 systems and a program manager survey of 41 U.S. weapon system development programs. In both cases, conceptual and empirical data were collected. The conceptual information supported development of a conceptual framework for analyzing prototyping strategies. The empirical data supported a thorough analysis of past prototyping experience. Policy recommendations are derived from both aspects of this research.

The evidence suggests that the lack of a clear definition of prototyping has contributed to a lack of consensus on prototyping policy. We have defined a prototype as hardware or software that allows hands-on

testing in a realistic environment. But the most critical characteristic of a prototype is its intended use: A prototype is intended to generate information useful in assessing and reducing risks and improving the quality of acquisition decision making. Hence, in scope and scale, it is *representative* of a concept, subsystem, or production article with potential utility. A prototype is not a complete system, but rather it focuses on selected areas of high risk that are essential to system success. This definition is broad because the range of risks and decisions that prototyping can address is broad. This is reflected in the wide spectrum of prototyping experience documented in this report. Similarly, that experience suggests that prototyping strategies—the way in which prototyping activities relate to the larger acquisition strategy for a system—have also varied widely in their application. Given this variability, it is no wonder that a consensus on prototyping policy is difficult to achieve.

THE NATURE AND ROLE OF PROTOTYPING

The conceptual framework developed as part of this research identifies three basic elements of a prototyping strategy: goals, timing, and integration. These were measured here as purposes and objectives of prototyping, the phase in which prototyping occurred, and the level of integration of the prototype relative to a full production article. There is considerable program-to-program variation across those dimensions, indicating that prototyping is not a single approach but rather a complex set of strategies that differ across many dimensions. These strategies vary widely in kind—from an emphasis on demonstrating that a technology is mature enough to be incorporated into a weapon system to demonstrating that a particular combination of system design and technology meets operational requirements.

A few prototyping strategies appear to be most common. For instance, prototyping activities with goals of technology demonstration usually occur earlier in a program and are performed at the partial system level, with just enough integration to demonstrate the relevant new functions. On the other hand, goals that focus more on assessing the performance of a system design in meeting an operational need tend to be associated with prototyping activities performed at the full system level (higher degree of integration) later in the acquisition cycle. Additionally, achievement of some goals often precludes achievement of others.

There are few identifiable differences in prototyping strategies and their application between services or across weapon types. Apparently, differences in the technical characteristics of systems, management style, and institutional structure are not major drivers of observed differences in prototyping strategies. The application of a particular prototyping approach was more a function of the purposes and objectives of the prototyping activities, which in turn was a function of the type of risks and uncertainties that exist in the program.

Detailed programmatic characteristics, such as contract type, requirements specification, number of prototypes, decision layers, and amount of documentation, are loosely associated with the basic strategy elements. There are myriad detailed programmatic characteristics that both contribute to defining a particular strategy and account for the considerable variation in the specifics of prototyping strategies. For the most part, these detailed programmatic characteristics flow from the basic elements of prototyping strategy: the goals, timing, and integration level of the prototyping activities.

Macro-level strategies have been fairly constant over time, though some factors may have changed at the detailed level. There are some indications of minor change: focus on more mature technology and demonstrations of performance achievement rather than technical feasibility. But the evidence suggests that prototyping strategies of the past are for the most part just as common today, despite changes in the acquisition environment.

Prototyping strategies do not seem sensitive to factors that we might expect to affect them. The number of prototypes fabricated and tested does not seem to vary across the different combinations of purposes, objectives, integration levels, or program phases. Similarly, macro-level prototyping strategies appear to be only slightly related to the cost and schedule aspects of a program.

PROTOTYPING AND PROGRAM OUTCOMES

The effect of prototyping on program cost, schedule, and performance outcomes is ambiguous. We might expect that the information generated through prototyping activities would reduce program risk as compared to nonprototyping programs. Assuming incorporation of the information into program plans and baselines, prototyping program outcomes should be relatively closer to baseline estimates. However, there are few significant differences between prototyping and nonprototyping programs with respect to cost growth, total actual program duration, or schedule slip. Similarly, it is not possible to generalize about the effects of certain types of prototyping strategies relative to others. We do not know enough about the mechanisms through which prototyping affects program outcomes to be able to establish a relationship between prototyping strategies or programmatic characteristics and particular outcomes, nor do we know how to distinguish those effects from the myriad of other factors that may influence program outcomes.

POLICY IMPLICATIONS

The research questions explored in this analysis fall under the umbrella policy goal of establishing criteria for prototyping: deciding whether or not to prototype, and if so, how. This analysis suggests that attempts to define such a policy at any but the broadest levels should be avoided. Program-specific characteristics and the characteristics of the acquisition environment vary so widely that no generic criteria are apparent to determine whether or not to prototype or what kind of prototyping strategy to pursue. Thus, it is not possible or even desirable to develop a set of firm decision rules. Nonetheless, based on the research reported here, we can say something about what broad acquisition policy with respect to prototyping *should* be.

The basic policy guideline might require program managers to assess the extent to which prototyping is both useful and appropriate in a particular case. In essence, this requires an evaluation of the relative costs and benefits of prototyping for that application. In terms of dollars, this might be stated as weighing the cost consequences of proceeding into a subsequent acquisition phase with a poor design against the cost of the prototyping strategy. Of course, determining the cost consequences of proceeding with inadequate information (e.g., cost risk) is not a trivial exercise. Similarly, the fundamental consideration might be stated as a trade-off between the net benefits of prototyping and the type and magnitude of risk in a development effort. Hence, prototyping policy might require evaluating and balancing several factors: the relative technological advance in a system, uncertainty regarding the utility of a new concept, the maturity of the technology being incorporated, and cost and schedule constraints. Unfortunately, there is no way to consistently measure those dimensions. Further, even if we could accurately measure the relative technological maturity of a system design, for instance, we still do not know how much weight to give any single factor in the overall decision calculus. In the end, there is no substitute for informed judgment made by experienced managers and engineers.

ACKNOWLEDGMENTS

This report greatly benefited from the efforts of numerous RAND colleagues. Giles Smith, Michael Rich, Ronald Hess, John Birkler, and Thomas Glennan provided helpful comments on early drafts. Mitchell Wade ensured that the structure and logic of the document were both transparent and consistent. Laural Hill was invaluable in developing the program manager worksheet. William Stanley and Richard Heppe provided thoughtful and constructive technical reviews, resulting in a much improved product. Remaining errors are the sole responsibility of the author.

I would also like to thank the numerous government and industry officials who provided their time for discussions of prototyping, and who participated in the survey that forms an important part of the database used in this study.

This report is dedicated to Robert Perry, the project leader of the initial research effort. His early work in this area underlies much of this research.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

This report explores the nature of prototyping, analyzes the role it plays in weapon system development, and extracts lessons for acquisition policy making. Prototyping can be simplistically defined as the fabrication and testing of hardware or software at some point in the acquisition cycle prior to commitment of full rate production. (This research adds precision to that definition of prototyping.)

The use of prototyping in weapon system development has been cyclical. Prototyping of aircraft engine-airframe combinations was the customary pattern of aircraft development before 1940 and was fairly common into the 1950s. With the advent of the "total system concept" in the early 1950s, the use of prototyping in U.S. weapon system development declined. The pattern again reversed in the late 1960s when (then) Deputy Secretary of Defense Packard instituted a "fly-before-buy" acquisition strategy, which emphasized hardware demonstrations before production start. However, the military services resisted the policy, and it was not fully accepted and applied.

In the mid-1980s, U.S. interest in the use of prototyping in weapon system development again surged: The 1986 Packard Commission report emphasized that prototyping before commitment to full-scale development would enhance source selection, provide early demonstrations of the feasibility and operational utility of new technologies, and improve initial cost estimates of new systems.[1] Congress also began to encourage prototyping of weapon systems, and in 1987 prototyping formally became a part of Department of Defense (DoD) acquisition regulations.[2] Nonetheless, basic questions concerning the nature of prototyping, under what conditions one should prototype, and the benefits of prototyping remain unanswered.

The changing acquisition environment may also imply changes for prototyping strategy. In the past, fairly complete systems could be prototyped at a reasonable cost. But as weapons become more complex, prototyping full-scale, fully integrated systems may no longer be feasible or even beneficial. The nature of the technical challenge has also changed; in aircraft, increased emphasis is being placed on inte-

[1] *A Quest for Excellence*, Final Report to the President by the President's Blue Ribbon Commission on Defense Management, June 1986.

[2] DoD Instruction 5000.2, "*Defense Acquisition Program Procedures*," September 14, 1987.

grated electronics, economical supercruise, agility, and low observable characteristics; in tanks, emphasis is on armor, gun aiming, and armor penetration. The simultaneous introduction of these new technologies and changes in emphasis among the various performance characteristics (e.g., emphasizing stealth) seem likely to increase technical integration risks and suggest that there might be corresponding changes in the appropriateness or application of prototyping strategies. Additionally, the projected decline in defense budgets and the associated decrease in new major system starts suggest a new role for prototyping in the future: as a way to keep design teams together and continue to advance the state of the art in weapon system technologies.[3] To devise prototyping strategies that will meet these new challenges, we must first understand the nature, role, and impact of current prototyping efforts.

OBJECTIVES

Whether or not to prototype—and, if so, how—is an important decision in the acquisition process, with implications for program cost, schedule, and performance outcomes. But that issue cannot be resolved—or even fully addressed—until more basic questions are answered. Confusion and ambiguity in the use of the term *prototype* has been a major contributor to the lack of consensus for the use of prototypes in weapon system development. What is a *prototype?* Strictly the earliest, nonoperational, functionally representative test article in a development program? Or any test article built prior to production? Likewise, what distinguishes prototyping from other acquisition strategies? Is it one strategy, or several? And if several prototyping strategies exist, how are they different? What are their individual benefits and limitations?

This research begins to address these questions, and also begins to explore the policy implications of the answers to these questions. We have four objectives:

- Improve understanding of the fundamental nature and role of prototyping as an acquisition strategy in weapon system development.

[3]This proposal has appeared in several forms from several sources recently: a 1990 DSB Summer Study; "rollover" policy as proposed by Representative Les Aspin; Paul H. Richanbach et al., *The Future of Military R&D: Towards a Flexible Acquisition Strategy*, Institute for Defense Analyses, July 1990, P-2444; U.S. Congress, *Restructuring Defense: Transitioning the Defense Industrial Base*, Office of Technology Assessment, July 1991.

- Examine the most common prototyping strategies and how they have changed over time.
- Investigate the relationship between prototyping and program outcomes.
- Make recommendations on what kind of policy, if any, DoD should have regarding the use of prototyping in weapon system development.

The first objective constitutes the major research focus. It is oriented toward developing an operational definition of *prototype* and *prototyping strategy*. This includes distinguishing prototypes from other hardware used for testing, and differentiating prototyping strategies from other acquisition strategies (e.g., conventional development-production or concurrent development-production approaches). Generally, improved understanding of prototyping as an acquisition strategy can be attained only by answering these initial questions. Development of a conceptual framework and characterization of past prototyping activities is an integral part of the research addressing those questions. This objective attempts to crystalize the concept of prototyping and its place in weapon systems development, thus enabling more consistent and informed policy making regarding its use.

The second objective takes the research past the development of a conceptual framework and begins to address policy issues. We are interested here in identifying the more common prototyping strategies, if any. We also begin to address the issue of the extent to which prototyping strategies need to be changed to reflect changes in the acquisition environment. Technical, political, and economic changes in the acquisition environment (e.g., subsystem integration, increased program oversight, and declining R&D budgets) suggest that past prototyping strategies and associated benefits may not be entirely appropriate in the current environment. Identifying how prototyping strategies have changed over time is a first step toward assessing whether past prototyping strategies are relevant to the new environment.

The third objective attempts to provide some insight into the relationship of prototyping and program outcomes. Previous research has demonstrated that prototyping can be a valuable approach to weapons development; at least for some programs, it has reduced cost growth, schedule slippage, and performance shortfalls.[4] It has also enabled decision makers to make better-informed decisions. Though this study does not assess the value of prototyping per se, it addresses related questions: Does prototyping add time to program schedules? Is prototyping associated with lower cost growth and schedule slip outcomes? What are the mechanisms for such an effect? Prototyping policy should be based on knowledge of the relationship between prototyping and program outcomes.

The fourth objective, making policy recommendations, describes what DoD prototyping policy might look like, how it relates to other acquisition policies, and how it might be implemented. The ultimate goal of such research is to produce criteria that would define when and how prototyping should be used in weapons development—a particularly important task now. given the changing nature of military systems, inventories, and shifts in acquisition-spending patterns. We are attempting to produce a tool that will help decision makers determine whether or not a prototyping strategy is worthwhile in a specific instance. While this research stops short of providing actual criteria or specifying a detailed policy, it does offer a conceptual outline of how prototyping policy should evolve.

GENERAL APPROACH

Prototyping is only interesting as a policy issue to the extent that prototyping is likely to significantly influence program outcomes. Thus a comparison of prototyping and nonprototyping programs is required. While other research has performed such comparisons using a case study approach, there are few examples of this type of analysis using a larger, broader-based sample.

This research uses a large sample size approach in an attempt to better understand the nature of prototyping and its role in weapon system development. In this approach, some detail is sacrificed to enable a study of broader scope. A limited number of variables, specified in advance, is collected for a large number of programs, and subjected to statistical analysis. While the broader scope and macro-level perspective of this large sample approach is more conducive of policy formulation, it is unsatisfying in the sense that cause-effect relation-

---

[4]See Edmund Dews et al., *Acquisition Policy Effectiveness: Department of Defense Experience in the 1970s*, RAND, R-2516-DR&E, October 1980; Karen W. Tyson et al., *Acquiring Major Systems: Cost and Schedule Trends and Acquisition Initiative Effectiveness*, Institute for Defense Analyses, March 1989, P-2201.

ships cannot be determined. The factors affecting the type of prototyping strategy chosen, and the effect of that strategy on program outcomes, cannot be definitively known.

Case studies, on the other hand, provide considerable detail regarding the role of prototyping in a few specific programs.[5] Alone, this approach is unsatisfying in the sense that the results are not necessarily generally applicable; it is difficult to formulate general policy from a few case studies. However, case studies do allow identification of the factors affecting the type of prototyping strategy used and help us better understand the relative success of that strategy.

While neither approach alone appears wholly satisfying, together they provide a firm basis for policy making. The large-sample empirical approach adopted here has not often been used with respect to prototyping. We can answer questions regarding what a prototype is, how it has been used in the past, and how the components of prototyping strategies relate to each other. We cannot answer questions about the appropriateness of given prototyping application, or its specific effect on a program. Hence, a case study approach is also needed to accurately answer those questions. We do include a limited comparison between prototyping and nonprototyping programs with respect to certain measurable program outcomes (cost growth, program duration, schedule slip) in order to gain some macro-level insight into the effect of prototyping on program outcomes, but these results cannot be definitive. Since the research is not complete in itself, only limited, macro-level policy implications can be drawn from the analysis.

Much of the information used here comes from various sources in publicly available literature. Many different journals and reports were reviewed in an attempt to compile a list of prototyping activities since 1960, both foreign and domestic, and synthesize the wide range of concepts and philosophy surrounding the use of prototypes in acquisition. Because much of the literature is ambiguous, a formal survey of government program managers was also conducted. This survey provided more detailed and better quality information on the characteristics of prototyping strategies that both supplemented and substantiated the data derived from the literature. Additionally, a database containing cost and schedule information on a large number

[5]See for example G. K. Smith et al., *The Use of Prototypes in Weapon System Development*, RAND, March 1981, R-2345-AF; and Mark A. Lorell, *The Use of Prototypes in Selected Foreign Fighter Aircraft Development Programs*, RAND, R-3687-P&L, September 1989.

of programs, both prototyping and nonprototyping, was used to explore the relationship of prototyping to program outcomes.[6]

REPORT ORGANIZATION

The remainder of this report presents the results of the analysis. Section 2 defines *prototype* and *prototyping*, discusses several related concepts, and develops the conceptual framework to describe and analyze prototyping strategies. Section 3 outlines the study design and data used to analyze prototyping experience. Both published and survey data are included. Section 4 presents the basic findings relating to general prototyping strategies and analyzes variations in their basic elements and trends over time. Section 5 attempts to relate prototyping to cost and schedule outcomes, including some comparison with nonprototyping programs. Section 6 draws policy implications from the lessons learned in this analysis and presents further observations on prototyping policy. While this section stops short of providing specific guidelines for the use of prototyping in weapon system development, it does describe the characteristics of a robust prototyping policy.

Three appendices contain supplemental information. For readers interested in the mix of programs used in this research, Appendix A provides the lists of programs included in the analysis, both the literature review and survey databases. Appendix B contains more detailed tables and graphs, which document some additional results of the program manager survey and the literature review. These data supplement the data in Section 4 on the characteristics of prototyping strategies. Appendix C reprints the program manager worksheet, the survey instrument used to collect information from program managers.

---

[6]This database is derived from *Selected Acquisition Reports* and is based on ongoing research by the author.

2. A CONCEPTUAL FRAMEWORK FOR PROTOTYPING

Consistent policy formulation regarding the use of prototyping in weapon system development requires some agreement on what prototyping means. A cohesive framework that captures the variability of prototyping concepts and relates that variability to the characteristics of prototypes, the development process, and the acquisition environment has been lacking. This section is an effort to construct such a framework. The goal is to provide a structure that enables improved decisions on the use of prototyping in development programs.

This section begins by defining *prototype* and *prototyping*, then proceeds to develop the framework that will be used throughout the analysis. The framework is based on an extensive literature review, discussions with knowledgeable industry and government personnel, and the analysis presented here. It identifies the most important characteristics of prototyping programs, and, combining them, it divides prototypes into several categories. Like any attempt to simplify a large and highly variable body of data, this taxonomy is somewhat imprecise. Yet each category defines a group of prototyping strategies that offers unique benefits and brings unique limitations. By using this framework to analyze past development programs, we can learn how to use prototyping most effectively. For example, one class of prototype may be helpful for a given type of program while another class would be not only less useful, but even counterproductive.

DEFINING TERMS

Before we can distinguish prototypes from one another, we must first distinguish them from everything else. The most inclusive definition of a prototype is "hardware used for testing." This definition is not useful for acquisition policy, however, because it fails to distinguish prototypes from the hardware test articles often built during full scale development (FSD) or production. Neither advocates nor critics of prototyping mean to include these test articles in the debate.

What, then, defines a prototype? One source describes it as a tool for reducing technological uncertainty, particularly with respect to cost, schedule, performance, tactics, and integrated logistics support.[1] For aircraft, this definition translates to an engine-airframe combination that approximates the main features of a proposed operational aircraft.[2] An alternative definition holds that a prototype is "a vehicle or component the primary purpose of which is to test a design concept and obtain the information necessary for making sound decisions. . . ."[3]

The benefits commonly ascribed to prototyping imply support for both positions. The benefits listed in Table 2.1 (distilled from various sources) have a common theme: Prototypes generate information in order to reduce risk.

Since both prototyping and FSD test articles provide information to reduce risk, however, an additional dimension is needed to distinguish between them. That dimension is the intended use of the information. As one definition explains, a prototype is built in the

Table 2.1

Perceived Benefits of Prototyping

Frequently Mentioned Benefits
- Reduces technological risk and uncertainty
- Enables better quality decisions regarding trade-offs between cost, schedule, and performance
- Permits changes to be incorporated early in the program
- Identifies system interfaces and key technical problems
- Permits improved estimates of cost, schedule, and performance
- Increases design options
- Permits earlier testing (development and operational)
- Provides a hedge against threat uncertainty

Other Possible Benefits
- Cost effectiveness (if funding is austere)
- Improved visibility of logistics support and life cycle costs
- Improved response time to changes in threat
- Lower tooling and retooling costs
- Improved government contract negotiating position
- Less government oversight in competitive environment
- Sequential development and testing

---

[1]Robert Perry, *A Prototype Strategy for Aircraft Development*, RAND, RM-5597-1-PR, July 1972.

[2]Ibid.

[3]B. H. Klein, T. K. Glennan, and G. H. Shubert, *The Role of Prototypes in Development*, RAND, RM-3467-PR, February 1963.

expectation of change.[4] The information that it generates affects decisions on source selection; cost, schedule, and performance trade-offs; operational utility; and the major program phase milestones. This implies that the results of prototyping will be included in a major technical or programmatic decision prior to the production decision. One possible decision is program termination. Such flexibility in decision making is not often found during testing of FSD articles.

Thus we have a fairly robust definition: *a prototype is a product (hardware and/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 merely to demonstrate satisfaction of contract specifications.* The expectation (and acceptance) of change allows the information generated by the prototype to be included in major decisions affecting both risk management and the outcome of the program.

A prototype is not a complete system in the sense of being deployable to operational forces. Rather, a prototype focuses on selected areas of high risk that are essential to system success. Additionally, the desire to minimize the cost and time of prototyping suggests that limitations in nonessential areas are acceptable. For example, a prototype aircraft may not be designed to sustain the higher level of lifetime flight hours as an FSD or production article.

So the distinction between prototypes and other test articles lies in the purpose of the device, the information gained through testing, and how this information is meant to be used in the decision process. *Prototyping*, the strategy of using prototypes in the acquisition process, can be defined in the same way. It is the strategy of using test articles to generate knowledge intended to reduce identified risks and uncertainties.

Prototyping is an alternative to other acquisition strategies, such as a conventional development-production approach, and can supplement other kinds of analysis (e.g., wind tunnel tests). A conventional or concurrent development-production approach differs from a prototyping approach in terms of the relative timing of test information availability and programmatic decision making, and the nature of those decisions. In conventional development-production programs, the intent to transition to production as rapidly as possible is inherent in program planning at the time the development contract is awarded.

---

[4]Perry, July 1972, p. 5.

Test articles built during development have the sole purpose of demonstrating achievement of contract specifications. In contrast, a much wider range of risks are addressed in prototype testing, generating information that informs a wider range of decisions, including the decision to continue development or terminate the program. While there is some overlap, the basic distinction concerns the *intent* to use prototype test information for a broader set of more fundamental decisions.

CLASSIFYING PROTOTYPING STRATEGIES

The next step is to construct a taxonomy, a scheme to classify the various kinds of prototypes. That effort begins by identifying the important characteristics that have been used to classify prototypes. Like attempts to define prototyping, most previous efforts to classify prototypes have focused on their use.

Many classification schemes are possible based on the many different uses and characteristics of prototyping. For instance, an advanced prototype can be used to "verify and reduce the technology" of hardware, evaluate operational concepts, and provide alternative choices, while a production prototype reflects full production design details and is built using hard tooling.[5] Critical subsystem prototyping involves development of critical components and subsystems independently from full system prototyping.[6] Categories of prototypes are often associated with the development stage in which they occur, reflecting both degrees of system or technological maturity and a spectrum of program uncertainties. Notably, many of these categories correspond well with the intent of a DoD regulation.[7] Yet another possibility is to group prototypes by goal. These might fall into three separate categories: increasing development efficiency, improving the quality of decisions, and hedging against uncertainties. Achievement of one of these goals is not necessarily exclusive of other goals.[8] It is interesting that these goals are a restatement of those commonly attributed to prototyping (see Table 2.1).

---

[5]David Packard, "Improving R&D Management Through Prototyping," *Defense Management Journal*, July 1972, p. 5.

[6]Michael A. Pearce, *Prototyping: A Strategy for the Acquisition of Naval Aircraft*, Defense Systems Management College, 10 November 1976.

[7]MIL-STD 250A. This regulation defines exploratory, advanced development, engineering development, preproduction, and production models.

[8]G. K. Smith et al., *The Use of Prototypes in Weapon System Development*, RAND, R-2345-AF, March 1981.

Clearly, prototypes can be classified across a number of dimensions, many of which are also program characteristics. A representative list—by no means exhaustive—might include the following dimensions:

- Type of risk: *technical*—technological feasibility; *target*—"reducing a military need to cost, schedule, and performance goals"; *internal*—program management; and *process*—funding and approval.[9]
- Degree of risk: magnitude, seriousness, and importance of the various types of risk.
- Level of system integration: indicates what portion of the key subsystems are in the prototype in their final functional form.
- Program phase in which prototyping activities occur: reflects type and timing of information availability.
- Austerity of funding and management: how narrowly focused the effort is, and how much flexibility the sponsor allows the contractor in making trade-offs.
- Degree of production expectation: intent to produce and deploy system.
- Degree to which technical, performance, and mission requirements and objectives are specified: whether point goals are written into the contract or whether "best effort" or performance range is acceptable.
- Form with respect to final design and configuration: indicates the representativeness of the prototype.
- Tooling: soft vs hard.
- Decision affected: can be any technical or milestone decision prior to full-rate production.
- Budget category: basic research (6.1), exploratory development (6.2), advanced development (6.3), and engineering development (6.4).
- Degree of management flexibility: reflecting ability to make cost, schedule, and performance trade-off decisions at the program office and contractor level.
- Documentation and reporting requirements: reflecting need for tracking, coordination, and accountability.

---

[9]These risk categories are defined in William E. Thompson, III, "Risk Implications for Cost Growth in Weapon System Acquisition," *Concepts—The Journal of Defense System Acquisition Management*, Spring 1982, Vol. 5, No. 2.

- Quality of labor: relative to the production phase.

There are strong relationships among these dimensions. The type and degree of risk, for example, affect the phase in which the prototype occurs and the subsequent decisions. Austerity is reflected in funding and management flexibility. Production expectations and tooling are also closely linked.

GOAL: A NEW DIMENSION

Our objective is to create a framework that includes most of the critical dimensions that define a prototyping strategy, yet remains simple enough to be useful in decision making. We suggest three key elements: timing, level of system integration, and goal. From the perspective of the framework, the type and degree of risk in large part determine the choice of timing, integration level, and goals, while the various other programmatic characteristics listed above (e.g., austerity, tooling, production expectation) flow from those choices. The first two dimensions are simple and widely used. Timing means the phase in which prototyping occurs, and it is related to the level of system or technological maturity. The level of system integration means the extent to which the prototype represents a production unit in scope and scale, and includes all necessary subsystems for operational deployment. The third element of our framework, goal, is not well represented in the literature on classifying prototypes. Because it requires more explanation, the remainder of this section will focus on this dimension, providing examples of weapon systems when possible.[10]

Figure 2.1 summarizes the conceptual framework developed thus far, and places the taxonomy of goals within it. Prototyping addresses various types of risk and uncertainty by generating information that improves the management of that uncertainty. The taxonomy presented in Figure 2.1 is a hierarchy. The first level concerns the overall purpose of prototyping in the program; the second, the specific objectives of particular prototypes. In decreasing order of detail, these two levels relate to the kind of information that prototyping generates, and together constitute what we refer to as the goals of a prototyping strategy.

---

[10]As described in Section 3, the program data come from available public literature and a survey of program managers and are deficient in many respects. In no case was there enough information to categorize a prototype with perfect confidence.

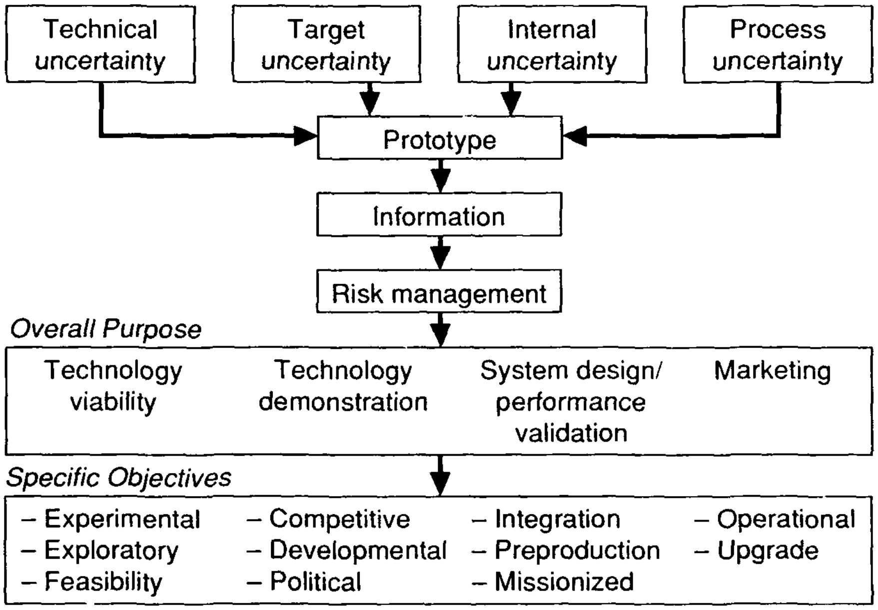


Figure 2.1—A Prototyping Taxonomy

Level One: Overall Purpose

The first level categories, denoted overall purpose, represent the general purposes of the prototyping phase and are the most aggregate classification level. Overall purposes are closely related to the expected benefits of prototyping and the decision stage of the program.

- *Technology Viability:* Generating basic technical information to reduce technological risk in a general sense. These are "building block" prototypes, intended to add to the general knowledge base. They generally occur very early in a program, often before demonstration/validation at Milestone I, or even outside the normal weapon system program structure. No military mission needs to be specified.
- *Technology Demonstration:* Exploring the possible performance envelope of a system. Prototypes in this category are often used to explore the usefulness of a new design or concept in performing a

specific mission, or to demonstrate a particular application of technology. They may also be used to generate or preserve design and concept options as a hedge against threat uncertainty. Missions or functional requirements are specified. These prototypes may occur early in the program in concept exploration or validation phases at a time when design is not frozen. Production of an operational system is often anticipated.

- *System Design/Performance Validation:* Involving design and performance specifications or requirements. Also included here are demonstrations of the ability to meet a specified threat, contract specifications, and producibility concerns. Missions are specified, often in detail, and there is an expectation of production. Operation, support, and logistics are also of concern. This category might also be called "engineering," since these prototypes are often fabricated as part of advanced development or full-scale development efforts.
- *Marketing:* Having to do directly with selling a product or supporting a proposal. These prototypes are often close to production configuration or are missionized. Competition is a frequent theme here. These can be part of any decision phase prior to production; they can also exist outside the program milestone structure. There is a definite expectation (or hope) of production. Missions do not need to be specified, though the prototype is oriented toward a specific functional requirement. These prototypes are sometimes funded by private industry.

Normally, only one *main* purpose is relevant to a single program. Which purpose that is depends on the ranking of the key uncertainties. Prototypes in the technology viability category are most often associated with basic technical uncertainties. Prototypes in the technology demonstration category are associated with both technical and target uncertainties. Almost any kind of prototype can be associated with internal program uncertainties. System design prototypes are more often associated with some forms of target and internal uncertainties. Marketing prototypes can address all four types of uncertainties.

Given the overlap between the various categories of risk and main purposes, it seems useful to allow for *secondary* purposes. Using the same set of categories as main purposes, the secondary purpose designation is intended to capture those aggregate level goals that may be less important than the primary purpose, but still represent an important focus of the prototype program.

Level Two: Specific Objectives

The specific-objectives level explicitly defines many possible uses for prototypes and recognizes that one prototype may serve several objectives, which can be ranked by importance. Additionally, each prototype in a development program may be associated with a different set of specific objectives. Specific objectives relate to the rationale underlying fabrication of the prototype and to the specific information generated. Eleven specific objectives are listed:

- *Experimental:* Demonstrates a new idea, a new technology, or an existing technology in a new application. This usually occurs very early in the program and may not have particular mission or production expectations.
- *Exploratory:* Evaluates the possible performance envelope or tests the feasibility of a performance requirement. May not have a mission specified or expectations of production, but does have explicit performance goals. This usually occurs in the concept or validation phase.
- *Feasibility:* Demonstrates performance objectives in reference to a specific mission. This usually occurs in the validation phase, though production may not be expected.
- *Competitive:* Used to improve source selection decisions in validation or FSD phases. Production is anticipated.
- *Developmental:* Determines tactical or operational suitability and utility for military uses. May occur in the concept or validation phases. This is the missionized version of an experimental prototype.
- *Political:* Achieves some political or corporate strategy objective, demonstrates attainment of a political objective, or responds to a politically established requirement. This can occur throughout the decision process, though it occurs most often in validation or FSD.
- *Integration:* Tests subsystem matching and full system operation. May be part of the concept, validation, or FSD phases. Specific mission or functional requirement exists.
- *Preproduction:* Tests production configuration after design freeze, usually during FSD. Producibility concerns are relevant. Full-rate production is expected.
- *Missionized:* Evaluates performance with respect to specified threat using fully integrated system. This may occur in concept, validation, or FSD phases.

- *Operational:* Tests operational suitability of fully integrated system, including reliability, availability, and maintainability characteristics. Also used for doctrine development and integrated logistics support planning.
- *Upgrade:* Tests or demonstrates subsystem improvement to existing system in operational use. Occurs either during the production phase of existing platforms or as a separate retrofit program. The upgrade itself may be part of a concept, validation, or FSD phase.

Notice that as we move down through the list of specific objectives, the prototype increasingly resembles final production configuration, occurs later in the program, is more fully integrated (i.e., includes a complete set of subsystems), and is less austere. Also note that two of the objectives, competitive and political, differ from the others fundamentally. These two relate more to the acquisition process and programmatic considerations than to technology.

It should also be noted that several previously mentioned potential benefits of prototyping are not explicitly included: improving cost and schedule estimates, allowing more informed trade-off decisions, and providing a hedge against threat uncertainty. Though we consider these benefits of prototypes as important as the rest, and a properly executed prototype program may actually satisfy those goals, in the current acquisition environment virtually no prototype program has these as a main purpose.

UNDERSTANDING THE FRAMEWORK

To understand how this taxonomy would be applied, consider several examples. The first National Aerospace Plane (X-30), which has as its goal to demonstrate the maturity of hypersonic flight technology, would be considered a technology viability prototype, with specific objectives relating to the experimental and feasibility categories. The tilt-rotor XV-15, a vertical takeoff and landing air vehicle, would be classified as a technology demonstrator prototype whose specific objectives were exploratory and developmental. The UH-60 Black Hawk helicopter would be classified as a system design/performance validation prototype; specific objectives included preproduction and operational goals, as well as competition. Northrop's F-20, a relatively low-cost multirole fighter aircraft, was a marketing prototype. Its specific objectives fell into the preproduction, competitive, and operational categories.

Under this framework, there are many different types of prototyping strategies, depending on the kind of risk involved and the decision to be affected. As noted above, each system has only one main purpose but may have several specific objectives. The idea of this taxonomy is to capture the basic rationale for building the prototype with the main purpose categories, then to define as many of the specific objectives as possible.

There are strong relationships between the elements of the framework with respect to the various dimensions and characteristics that define prototyping. For example, Table 2.2 indicates that certain specific objectives are intuitively associated with particular main purposes. That relationship results from the kinds of risk and uncertainty addressed in each purpose and objectives category, as well as the level of system integration and phase of the program. Similarly, some combinations of main and secondary purposes are expected to be more common than others. For instance, technology demonstration as a main purpose seems consistent with system design as a secondary purpose, but the combination of technology viability and marketing seems unlikely. There are also combinations of objectives that are intuitively more likely than other combinations. Experimental, exploratory, and feasibility are all related in that they concern technology and basic applications. Preproduction, missionized, and operational prototypes overlap to the extent that they reflect the full system. However, it is very unlikely that experimental and operational objectives would be found in the same prototype. The message here is that achievement of one particular objective may exclude achievement of some other objectives. In other words, prototypes are narrowly focused on specific issues important to a particular program, and thus are more likely to produce information useful to program managers.

Table 2.2

Common Purpose-Objective Associations

Technology Viability • experimental • exploratory	Technology Demonstration • feasibility • developmental
System Design/ Performance Validation • integration • preproduction • missionized • operational • upgrade	Marketing • political • competitive

As we have said, there is also a theoretical relationship between main purpose/specific objectives and the program phase in which prototyping occurs. Table 2.3 outlines this relationship by specific objective. Although there are situations when these relationships do not hold, the pattern is fairly clear. Experimental prototypes would not be expected to occur during FSD, and operational prototypes do not usually occur during concept exploration. Notice that prototypes never occur during production; by the time there is a commitment to production, most major decisions affecting design, technology, and operational utility have already been made.[11]

Another way to illustrate the relationships between the various specific objectives is to compare each objective in terms of the dimensions of prototyping listed earlier. Table 2.4 shows that similarity in prototyping dimensions implies some overlap in goals.[12] Notice in Table

Table 2.3

Interaction of Objectives and Process

	Process Phase		
Specific Objective	Concept (Milestone 0 – I)	Dem/Val (Milestone I – II)	FSD (Milestone II – III)
Experimental	X		
Exploratory	X	X	
Feasibility		X	
Competitive		X	
Developmental		X	X
Political			X
Integration			X
Preproduction			X
Missionized			X
Operational			X
Upgrade			X

[11]The exception is when a production facility or critical production tooling is prototyped in some form. Upgrades and modification programs would be classified with respect to the development stage of the subsystem being incorporated.

[12]There are always a few exceptions to any rule. For instance, while it may be clear that the goals of the National Aerospace Plane (NASP) program are properly classified as technology viability with experimental and feasibility objectives, it is also clear that NASP is not austere in terms of budget or management. Further, the NASP integration level is probably not "low" as might be implied by the chart; propulsion, aerodynamic shapes, and flight controls will need to be highly integrated. Thus it is demonstrated that properly classifying a given prototype involves consideration of its technical, political, and economic characteristics; the matrix in Table 2.4 is meant only to be suggestive.

Table 2.4

Specific Objectives and Prototyping Dimensions

Specific Objective	Risk Type	Degree of Risk	Austerity	Production Expectation	Extent Mission Specified	Extent Performance Specified
Experimental	Technical	High	High	No	Low	Low–Med
Exploratory	Technical	High	High	No	Low	High
Feasibility	Target	Med–High	Med–High	No	High	Medium
Competitive	Process/Intnl	Medium	Med–High	Yes	High	Medium
Development	Target	Medium	Medium	Sometimes	High	High
Political	Process/Intnl	Med–High	Med–High	Yes	High	High
Integration	Technical	High	Low–Med	Yes	High	Medium
Preproduction	Target	Medium	Low	Yes	High	High
Missionized	Target	Med–High	Med–High	Yes	High	Med–High
Operational	Target	Med–High	Medium	Yes	High	High
Upgrade	Tech./Target	Medium	Medium	Yes	High	High

Specific Objective	Tooling	Form with Respect to Final Config.	Level of System Integration	Phase Occurring	Budget Category	Management Flexibility
Experimental	Very soft	Not final	Low	Concept	6.1/2	High
Exploratory	Very soft	Not final	Low–Med	Concept	6.2	High
Feasibility	Soft	Close	Medium	Dem/Val	6.3	High
Competitive	Soft	Close	Medium	D/V, FSD	6.3+	High
Development	Soft	Close	Med–High	Dem/Val	6.3	High
Political	Semisoft	Final	High	D/V, FSD	6.3+	Medium
Integration	Semisoft	Close	Very High	FSD	6.4	Medium
Preproduction	Hard	Final	High	FSD	6.4	Low
Missionized	Soft–Hard	Close	High	D/V, FSD	6.3+	Medium
Operational	Soft–Hard	Final	High	D/V, FSD	6.3+	Medium
Upgrade	Semisoft	Close	High	Conc,D/V,FSD	6.3+	Medium

2.4 that objectives such as experimental and feasibility, or missionized and operational, are fairly close in terms of the dimensions; thus, those objectives overlap substantially. Also notice that objectives such as exploratory and preproduction are at opposite extremes, indicating for instance that a prototype with a main objective of demonstrating and exploring the reasonableness of a performance requirement will not have characteristics necessary to test the final production design.

VALUE AND LIMITS OF THE FRAMEWORK

The categorization of prototypes is a highly subjective exercise. It is useful only to the extent that we learn something about which characteristics of prototyping strategy are necessary to achieve specified goals. From the dimensions defined above, we can derive two major lessons: (1) prototyping strategies are focused on particular issues identified as key risks and uncertainties in the program, and (2) there are differences between prototypes and associated acquisition strategies that suggest that attainment of certain objectives precludes attainment of others.

It should also be noted that none of the above discussion is meant to imply that there are generic strategies that can be applied to defined circumstances. Each program is unique. While classification schemes are useful, an effective prototyping strategy must be tailored to reflect this real-world variation.

3. STUDY DESIGN AND DATA

This analysis included two separate data collection efforts—a literature review and a survey of U.S. government program managers. The resulting databases cover a large number of diverse programs and variables, and support a broadly scoped analysis of prototyping experience.

The literature review included a broad-ranging examination of prototyping concepts and issues, as well as a collection of general programmatic information on specific prototype programs. This supported the development of the conceptual framework described in Section 2 and the construction of a large database of programmatic information on 287 programs spanning the period from 1960 to 1988. Sources for this data are given in the bibliography, and the list of programs included in the database are provided in Table A.1.

The second data collection effort involved a formal questionnaire sent to government program managers. Responses from 41 programs allowed construction of a database of programmatic characteristics for those systems. This data includes both quantitative and qualitative information. To our knowledge, such a database has never before been developed. Table A.2 lists the programs that responded to the survey. The survey itself is reproduced in Appendix C.

METHODOLOGY

The conceptual framework presented in Section 2 provided guidance and consistency for the two data collection efforts. In both cases, information was collected that enabled exploration of relationships between programmatic characteristics that constitute prototyping strategies and allowed tracking of broad trends in those relationships. To a considerable extent, the data collected from both the literature review and the program manager survey were intended as a rough test of the reasonableness of the conceptual framework.

By design, the two databases are complementary, each having comparative advantages. The literature review produced programmatic data that, while insightful, were unsatisfying in terms of providing details of prototyping strategies. The survey was intended to obtain that additional detail, as well as gather supplemental data on the characteristics of prototyping programs and improve the quality of information available to analyze past prototyping experience. The survey asked for the same information that was generated as part of the literature review. Thus for certain sets of variables, the data and analysis for the literature review and the survey are directly comparable.

Many different journals and reports were examined in an attempt to compile a list of programs incorporating prototyping activities since 1960. Additionally, information relating to the characteristics of the prototype was collected. This information was used to categorize the prototype program within the framework developed previously. General program information was also of interest, including the program phase in which the prototype occurred, the management agency or agencies involved, and basic cost and schedule information.

The survey was composed of a worksheet questionnaire sent to 85 U.S. government program managers of current systems where there was some indication that prototyping was or will be used. We received 43 responses for 41 programs.[1]

The literature review can cover a very large number of programs, though in scant detail. The program manager survey has the advantage of collecting primary information, assessments, and opinions on current prototyping programs from the government participants. This mitigates any bias that might result from our interpretation of the literature; the bias in the survey reflects that of the respondents. The questionnaire covered more aspects of the programs in more detail, and included both quantitative and qualitative responses. The qualitative responses were particularly interesting as they reflected managers' experiences.

DATABASE DESCRIPTION

Table 3.1 indicates the range of information that was collected by both the literature review and the program manager questionnaire. There are three types of variables: quantitative (cost, schedule, etc.), categorical, and indicator. The questionnaire collected the same data gathered through the literature, plus considerably more on a wider range of programmatic characteristics. In all these cases, the measures used in both the literature review and the survey were identical.

[1]The Navstar Global Positioning System (GPS) program office provided three responses, one each for satellite, user equipment, and ground control segments of the program. Each had its own acquisition strategy, including contracting and development tasks.

Table 3.1

Variables Used in Analysis

Variable	Description	Included in Literature	Included in PM Survey
Program name	System designation	X	X
Position	Position of respondent		X
Experience	No. of years at position		X
Weapon type	System type classification	X	X
Management agency	Organization responsible for funding and management	X	X
Meaning	Meaning of term *prototype*		X
Distinguish	Difference between prototype and FSD article		X
Definition (1)	Survey-based definition		X
Definition (2)	Derived, narrow definition	X	X
Benefits	Expected benefits of prototyping		X
Effects	Expected effect on outcomes		X
Levels of prototypes	No. of prototypes by integration level	X[a]	X
Choice	Prototype level referenced		X
Program phase	Phase prototyping occurred	X	X
Main purpose	Main purpose of activities	X	X
Secondary purpose	Second-order purpose of activity	X	X
Specific objective 1	First-order objective where most of effort was expended	X	X
Specific objective 2	Second-order objective	X	X
Specific objective 3	Third-order objective	X	X
Specific objective 4	Fourth-order objective		X
Specific objective 5	Fifth-order objective		X
Specifications	Method of requirements specification		X
Performance mod	Requirement modification due to prototype testing		X
Contract type	Type of contract by program phase		X
Substitution	Prototyping as a substitute for other phases		X
Documentation	Relative amount of reporting		X
Layering	No. of decision layers by program phase		X
Decision maker	Office responsible for cost, schedule, performance decisions		X
Teaming	Teaming strategy indicator		X
Prototype cost	Cost of prototyping activities	X	X
Development cost	RDT&E[b] cost, including prototype	X	X
Procurement cost	Cost of total production	X	X
Total cost	Total program cost	X	X
Quantities	Prototype, FSD, and Production	X[c]	X
Program start	Year of program initiation	X	X
First operation	Year of first prototype operation	X	X
Design time	Months from program start to first prototype operation	X	X
Prototype phase	Months from program start to completion of test program	X	X

Table 3.1 (continued)

Variable	Description	Included in: Literature	Included in: PM Survey
Program length	Months from program start to first delivery of production unit	X	X[d]
Responsible office	Person who made decision to prototype		X
Timing	Whether decision was made before or after program start		X
Technological advance	Evolutionary or revolutionary		X
Challenge	Major technical challenge		X
Role of prototype	Role prototype played in meeting challenge		X
CAD/CAM	Whether CAD/CAM was used		X
Tooling difference	Difference between FSD unit and prototype fabrication		X
Skill level	Relative skill level of labor		X

[a]Literature-based data contain a single categorical variable; survey has one each for full system, partial system, subsystem, component, other.

[b]Research, develop, test, and evaluate.

[c]Literature data have prototype quantities only.

[d]Survey has calendar dates for the following: Milestones I, II, IIIa, IIIb, design start, fabrication start, first operation, test objectives achieved. Various intervals can be calculated.

This research postulated a few basic relationships and trends with respect to prototyping. We felt that prototyping strategies could be distinguished from other acquisition strategies; that they could be characterized by a few basic programmatic variables (e.g., goals, timing, and level of integration); that these basic elements are related to more detailed programmatic characteristics; and that prototyping strategies have changed over time as a result of a changing acquisition environment. Additionally, prototyping was expected to be associated with relatively better program outcomes in terms of cost growth and schedule slip.

The type of information collected in both the literature review and program manager survey relates to those postulates. Basic programmatic data on cost, schedule, decision process, and contracting strategies allow a basis for understanding prototyping as an acquisition strategy. Categorical variables relating to the definition of prototyping, expected benefits, and goals allowed characterization of specific prototyping strategies. The time-based information supports the objective of understanding the extent to which prototyping strategies have changed as the acquisition environment has changed. Data on program cost and schedule outcomes support a first-cut analysis of the effect of prototyping on those outcomes. Some of the variables listed in Table 3.1 are briefly described below:

- *Program name* is a tracking variable that allows identification of any outliers.
- The *position* and *experience* variables are used as data quality control checks for the program manager survey. For instance, the responses of a program manager who has been on the job for three or more years should qualitatively carry more weight than those of a manager who has less than one year of experience.
- The categories of *weapon type* used in the literature review database include fixed-wing aircraft, helicopters, land vehicles, missiles, subsystems, and other. The subsystem category includes guns, avionics, engines, etc. The other category includes space systems and ships. The smaller number of programs in the survey could reasonably support fewer categories: aircraft, helicopters, vehicles, electronic systems, and other.
- The *management agency* is simply the organization responsible for the program. Categories used in the literature survey include the Army, Navy and Marine Corp, Air Force, Defense Advanced Research Projects Agency (DARPA), joint U.S., other U.S., joint U.S./foreign, foreign government, foreign private, and U.S. private. The questionnaire uses the three U.S. services and a joint program category.
- The *number of prototypes* is the number of prototype articles fabricated. For competitive programs, this includes all contractors. The survey collected this information by level of integration as well as for the specific level of prototyping chosen for discussion by the survey respondent.
- The *level of integration* refers to the portion of the total system that was prototyped. There are three categories here: full system, which includes all key subsystems; partial system, which includes only one or two subsystems integrated into a platform (e.g., an engine-airframe combination); and subsystem, which includes subsystems prototyped independent of a platform.
- The *main* and *secondary purposes* and the three *specific objectives* are defined according to the taxonomy presented earlier.
- The *phase* identifies that part of the program (based on decision milestones) that incorporated a prototype.

- Two calendar dates are included: the *program start* date, determined as either the first decision milestone or when a technical development became focused enough to form a program office, and the date of *first prototype operation.*
- The *schedule data* show months from program start and were based on decision milestones or contract award dates.
- The *cost data* are in millions of constant dollars (FY82 for the literature data, FY89 for the questionnaire) and are used as a proxy for program size and level of effort. Actual reported costs or the most current estimates were used.
- The *definitional indicator* allows an important problem to be addressed: the variability in definitions used in the literature. Based on the more narrow definition of a prototype presented in the previous section,[2] programs were coded as either meeting this criteria, not meeting it, or providing insufficient information to support a finding.

Some data obtained in the survey were not available in the literature. Most of these concern either aspects of the programs potentially related to prototyping strategies (e.g., contract type, decision layers, amount of documentation) or asked the respondent to qualitatively describe the rationale behind prototyping in the program. For instance, questions regarding expected benefits, effects on program outcomes, and the difference between prototypes and other test articles resulted in responses that provide additional insight into prototyping activities. Those responses are reflected in the discussion in the following sections.

The data were coded in a way suitable for some basic statistical analysis, mostly frequency distributions and cross-tabulations. Because of the nature of the data collected, and the small number of observations for some subsets of the database, we relied more on simple correlations and evaluation of tables and graphs rather than formal statistical tests for significance, though we did perform those when appropriate.

[2]The general definition of a prototype used in this report is that it is an article fabricated in the expectation of change. This implies that the results of prototyping activities contribute to technical or programmatic decisions prior to full-rate production. A prototype has objectives other than only demonstrating satisfaction of contract specifications.

LIMITS OF THE STUDY

The data used here reflect several problems and limitations. First, the inconsistent use of the term *prototype* in the literature affects the quality of that data. Because of the very large variance in definitions, corrections could not be made without degrading the data. Therefore, programs were included in the database if one or more sources indicated that the program incorporated prototyping activities of some kind. This problem is partially resolved by the definitional variable described above.

There are also considerable gaps in the data. Very few programs have complete information of relatively good quality for all variables. This means that for some of the analysis, particularly that focusing on trends in the cost and schedule variables, there are few data points. To mitigate the small database problem, much of the analysis presented in Sections 4 and 5 uses the data generated through the literature review. This larger database is more amenable to statistical and graphical analysis. Nonetheless, the same analysis was performed on the survey data. Some of the more interesting or unique results are presented alongside the results of the literature review. Additional survey results are documented in detail in Appendix B.

Similarly, the list of post-1960 programs that constitutes the database used in the analysis is not complete, but it is representative of prototyping activities over the time period of interest. There are indications in the literature that there have been more prototype programs since 1960 than those listed in Table A.1. Additionally, since we collected information only on programs believed to include prototyping in some form, and examined only those that met a slightly more specific definition, we cannot know the relative frequency of prototyping versus nonprototyping programs.

Both the coding and the taxonomy are subjective. While this does not hinder the analysis, it does suggest that one must be careful when generalizing outside of the database and the assumptions used in the analysis. A few problems related to the general subjectivity of the taxonomy are worth mentioning. When coding the variable for integration level, a judgment had to be made regarding the representativeness of the prototype relative to the final objective system. This was complicated by the fact that any given program can include prototyping during more than one phase. In particular, programs that included a series of prototypes, each increasingly closer to production configuration, were difficult to categorize. These programs were categorized as partial system prototypes, reflecting an "average." This type of subjective coding problem was mitigated somewhat in the survey, which asked the respondent to specify which prototype (if there was more than one) was the object of the responses. Additionally, the schedule-related variables are subject to some uncertainty and inconsistency across programs. Identifying functionally equivalent milestones has proved to be a difficult task.

As mentioned earlier, the choice of research approach constrains both the kind of analysis that can be performed and the conclusions that can be drawn from it. The large-sample empirical analysis adopted here allows us to address questions concerning the components of a prototyping strategy, how those components relate to each other, and how prototyping strategies have been used in the past. We can also gain some insight into the factors affecting the choice of strategy, at least at the macro-level. We cannot address questions relating to the appropriateness of a specific prototyping application, or its effect on the program. Those questions require detailed case studies.

In spite of these limitations, an analysis of this type seems useful. To the best of our knowledge, this is the first time that such a large database of prototyping activities has been compiled, and it does yield some interesting insights into the nature of prototyping and its role in weapon system acquisition.

DESCRIPTION OF SAMPLE

The literature review yielded data on 287 programs spanning the time period from 1960 to early 1988. Programs were included if one or more sources in the literature indicated that the program incorporated, or will incorporate, prototyping activities, and if the first operation of the prototype article occurred in 1960 or later.

The prototyping worksheet questionnaire was sent to 85 U.S. government program managers: 43 responses were received, covering 41 programs. These programs were in various stages of development or procurement at the time the survey was conducted (May to October 1988). Of those 41 systems, 32 overlap the larger literature review database, though in some cases the prototype referred to in the survey is not the same as the one identified in the literature.[3] Nonetheless, the data are compatible in that the metrics used are similar.

---

[3]The nine programs not overlapping are: Advanced Attack Helicopter—Aircraft Survivability Equipment (AAH ASE), Mobil Subscriber Equipment (MSE), Forward Anti-Aircraft Defense Command and Control (FAAD C^2I), 9mm Pistol, Pershing II, Advanced Attack Helicopter—Automated Test Equipment (AAH ATE), Mk XV IFF, Short-Range Attack Missile (SRAM) II, IR Maverick.

As mentioned earlier, the criteria for including programs in the database present some definitional problems, as the term prototype is not used consistently in the literature. To reduce the influence of definitional inconsistencies, a variable was developed that allows the data to be sorted based on whether the program meets the more narrow definition of prototype begun in the previous section:

> A prototype is a product (hardware and/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 in the expectation of change, and is oriented toward generating information improving technical and programmatic decision making. It has purposes and specific objectives other than simply demonstrating that the article meets development contract specifications. The results of prototype testing are used in subsequent decisions, prior to the production decision, influencing system design and requirements formulation, operational utility, and cost and schedule estimates.

The definition was applied consistently within the limits of available data. For instance, programs in which production commitment was made at the same time as the development contract were not considered prototypes unless an article was fabricated and tested prior to the development contract award.

Figure 3.1 presents the distribution of this definitional variable for both the literature and survey data. The dominant result for the literature data is that for most of the programs, there was not enough information available to determine whether the article referred to as a prototype met the criteria. This result was expected, given the poor data availability regarding how the so-called prototype was used in the program. However, there were still enough programs that met the criteria to be significant. In the remainder of this analysis, unless otherwise stated, all results are for the total database. If the distributions for the programs that meet the narrow definition differ significantly from the total database, this will be indicated together with the direction of the change. We assumed that programs with insufficient information were still prototypes, but less information regarding the role of the prototype was available. It turns out there is essentially no change in the basic patterns and relationships examined in this analysis as a result of sorting by the definitional variable. The assumption appears to be supported.

Most of the survey respondents were prototyping programs as intended. Two definitional variables were constructed from the survey data. The first is a pure survey response: Ten programs claimed that

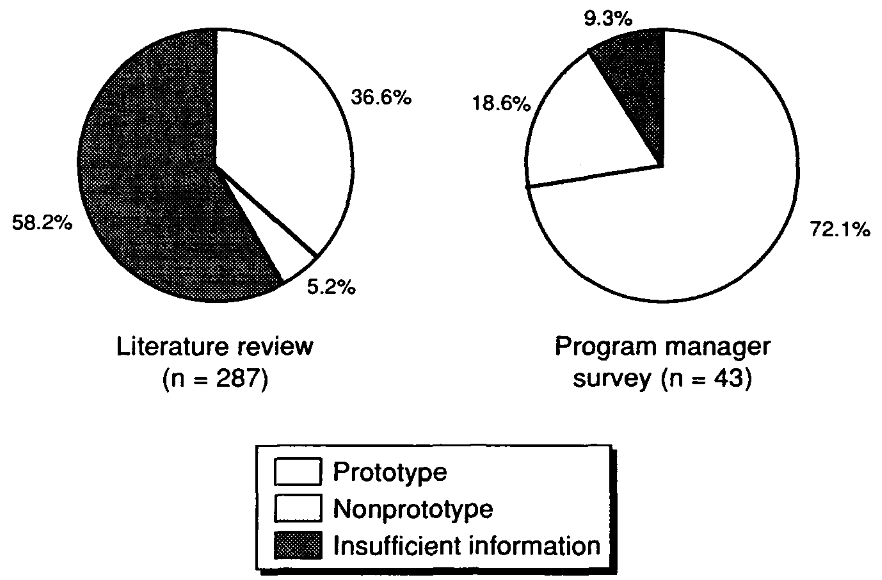


Figure 3.1—Distribution of Prototype Definition Designation

no prototyping occurred during development. The second (shown in Figure 3.1) is identical to that used in the literature survey: In this case, four programs provided insufficient information to make a judgment, and eight were definitely not prototyping programs.[4] Much of the survey data presented here represent only the 31 programs that meet the strict definition of prototyping. This is because most of the nonprototyping respondents did not provide any other information. To the extent that the results using these 31 programs are similar to those of the literature review, the treatment of the literature review data with insufficient information is valid.[5]

---

[4]The eight nonprototyping programs were FAAD Command and Control, Advanced Attack Helicopter—Automated Test Equipment, F-14, Trident II missile, T45TS, Defense Support Program (DSP), C-17A, and Joint Surveillance Target Attack System (JSTARS). The four programs with insufficient information were IR Maverick, Light Airborne Multipurpose System (LAMPS) Mk III, Submarine Advanced Combat System (SUBACS), and Mk-50 torpedo. If anything, these four programs appear to be nonprototyping programs. It is interesting that the V-22 system claimed no prototyping, but the responses continually made reference to the XV-15 tilt-rotor technology demonstrator, thus meeting the definition of prototyping used in this analysis.

[5]As discussed in more detail in Section 4, the survey results are entirely consistent with the results of the literature review. This validates the treatment of the literature review data. In any case, the actual numbers presented in the various tables are much less important than the patterns and relationships they illustrate. These relationships are consistent across many different cuts at the data, implying that the results are fairly robust.

The literature data provided a fairly good distribution across weapon types, dominated by fixed-wing aircraft, as Figure 3.2 shows. (The large number of fixed-wing aircraft in large part reflects the interest at RAND in aircraft systems, as much of the data used here comes from both published and internal RAND studies.) However, the distribution does support examination of differences in prototyping strategies across weapon system types. Figure 3.2 also shows a similar system-type distribution for the survey, dominated by missiles, aircraft, and electronic systems.

Figure 3.3 shows the frequency distribution across the organizations responsible for program management. All three U.S. services are well represented in both the literature and survey databases, allowing us to test the hypothesis that prototyping strategies differ across management agencies. Note that a significant proportion of the systems in the literature data are privately funded, either by U.S. or foreign firms. Interestingly, these private ventures are spread almost equally across the various system types, indicating a wide spread of interests and willingness to fund prototyping activities. All of the joint programs in the survey were Air Force led.

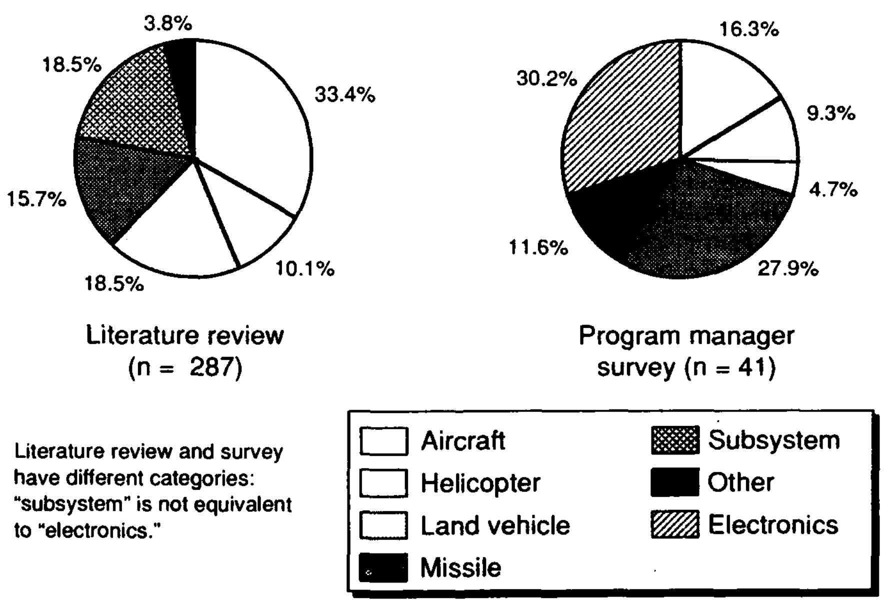
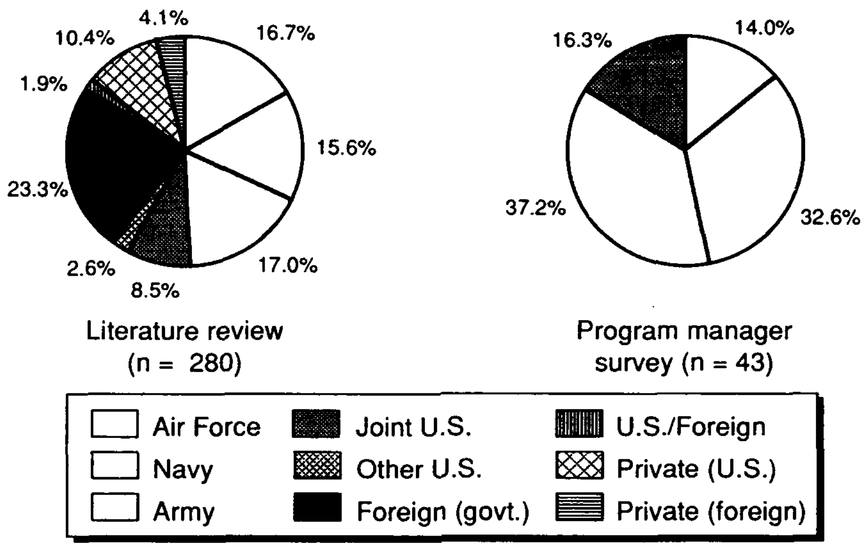


Figure 3.2—Sample Distribution by Weapon System Type



The survey was administered only to U.S. government program managers, therefore, there are no private industry or foreign categories.

Figure 3.3—Sample Distribution by Management Agency

The distribution across time of programs in the literature database is shown in Figure 3.4, based on the year in which the prototype was first operated. The median (50th percentile) is 1982 for this data set. The database includes more systems in more recent years. There are several reasons for this. First, the more recent data are more readily available. Second, and related to this, interest in prototyping has been increasing over the last few years. Third, because prototyping fell out of favor in the 1960s and late 1970s, the term may not have been used even if developmental activities were similar to what we call prototyping today. Because of data gaps, the trend that this figure implies does not necessarily reflect prototyping activity trends. In fact, as mentioned previously, interest in prototyping tends to be cyclical. We are just now entering a period in which prototyping in one form or another is more common as a part of weapon system development. It should be noted that some of the prototypes shown here had not yet achieved first operation at the time these data were collected. For instance, neither the Advanced Tactical Fighter (ATF) nor the Light Helicopter (LH) prototypes had flown.[6]

[6]Both ATF prototype models (YF-23 and YF-23) subsequently flew in the fall of 1990.

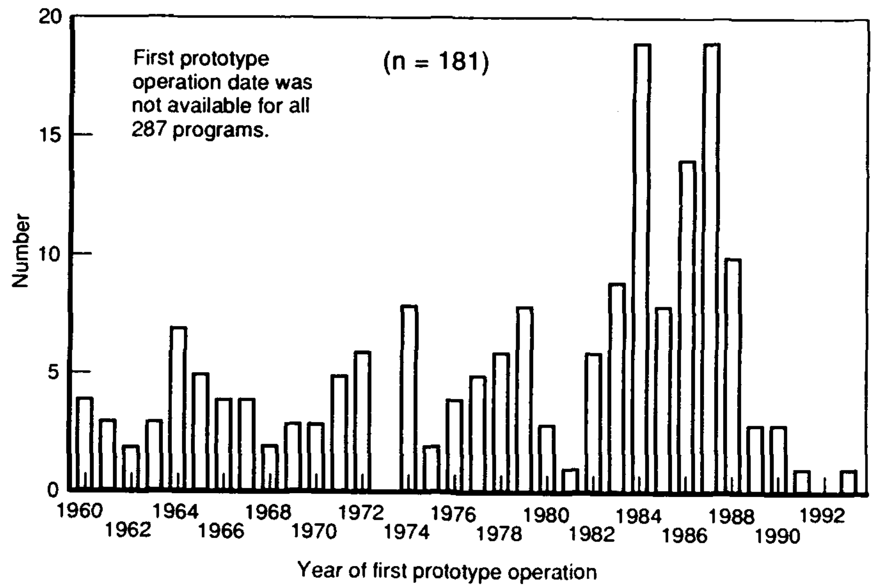


Figure 3.4—Distribution of First Operation Date (Literature Review Data)

Figure 3.5 shows the same distribution over time for the survey database. Again, there are more programs in more recent years (median is 1986), probably due to the nature of the survey sample: only current programs were surveyed, many of which began in the early or mid-1980s. As before, some of the dates shown here are estimated first-operation dates.

Table 3.2 shows summary statistics for the more quantitative variables based on the literature review data. These include the number of prototypes in a program, and the time- and cost-based variables. There are 146 programs in the database for which the number of prototype articles could be determined. The average across these programs is 5 articles, with a maximum of 33 in the Army's High Mobility Multipurpose Wheeled Vehicle (HMMWV) program, which involved a competition between three contractors, each submitting 11 prototype articles for testing. This is unusual for a land vehicle system—missile systems are more likely to have more prototype articles than other systems.

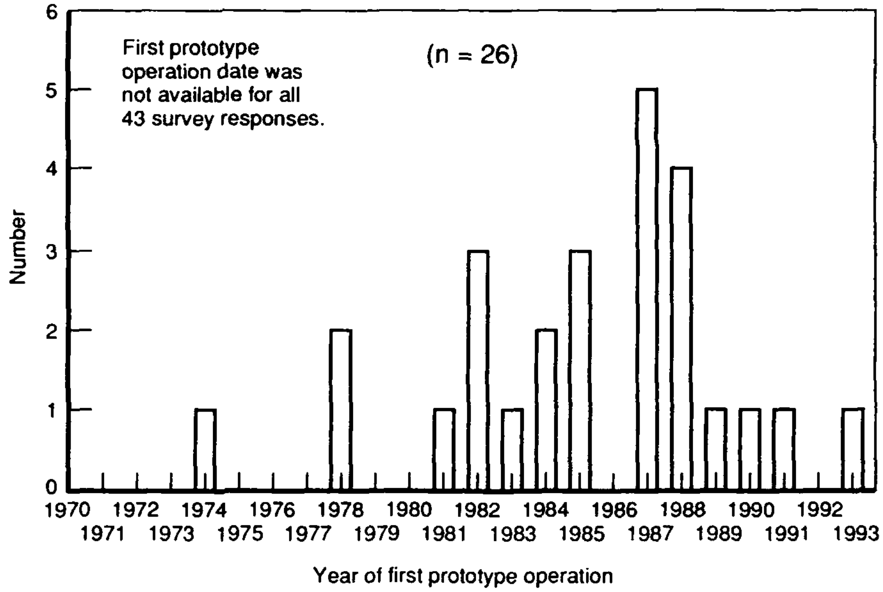


Figure 3.5—Distribution of First Operation Date (Program Manager Survey)

Table 3.2

Summary Statistics for Assorted Variables (Literature Data) (time in months from program start, costs in millions, constant 1982$)

Variable	Unit	No. of Obs.	Mean	Standard Deviation	Min.	Max.
No. of prototypes in program	number	146	5.1	5.5	1	33
Design time	months	90	29.0	17.1	5	99
Prototype phase time	months	26	46.9	20.9	12	84
Total program length	months	34	93.1	34.8	32	177
Prototype cost	$millions	25	190.2	260.8	2.1	1076.0
Development cost	$millions	49	1341.9	1627.9	21.4	9025.1
Procurement cost	$millions	47	5931.9	7209.8	30.0	33543.3
Total program cost	$millions	52	7332.1	8988.1	51.4	38936.2
Design as % proto time		25	60.5	16.4	18.7	89.5
Design as % tot. length		22	34.3	20.5	13.0	46.1
Proto as % tot. length		15	51.7	18.6	26.9	77.9
Proto$ as % RDT&E$		9	39.1	31.7	10.6	100.0
Proto$ as % proc$		10	15.5	31.3	0.6	103.1
Proto$ as % total$		10	7.2	8.2	0.6	26.3

SOURCE: Cost and schedule data are mainly derived from *Selected Acquisition Reports*. These were supplemented using data from articles cited in the bibliography.

The time-based variables (design time, prototype phase time, and total program length) are all calculated in months from program start, defined as Milestone I or the equivalent. Notice that design time (time from program start to first prototype operation) data were more available than the others, mostly because first prototype operation date is more easily identified than completion of the prototype test program. The ranges of these variables are considerable, though their relationship to each other is as expected. Design time is a subset of prototype phase time, which in turn is a subset of program length. Though the number of observations decreases when sorting by the definitional variable, the means and standard deviations are about the same.

The cost variables in Table 3.2 indicate high variability across programs. The prototype cost represents those costs associated only with the prototyping activity. It is a subset of development costs, which cover all research, development, and testing costs throughout the program. Procurement cost refers to the cost of production. Total program costs are the sum of development and procurement costs. The highest costs are associated with aircraft. The F-20 is the most costly prototype in the sample; this privately funded program included only costs related to building or demonstrating (marketing) the prototype. The current estimate (as of 1988) of ATF development costs represents the maximum development cost in the database. Procurement and total cost maximums are also aircraft—the F-16 and the B-1B.

The other variables listed in Table 3.2 are percentage variables calculated from cost and schedule information in the database. They clearly illustrate a data-availability problem, as indicated by the substantial decrease in the number of observations, particularly for the cost data. However, both the time and cost percentages seem reasonable. Design time is intuitively a large portion of the prototype phase time and a smaller portion of total program length. As expected, the cost of the prototype as a percentage of development, procurement, and total cost tends to decrease and is in the range of previous studies.[7]

Table 3.3 shows similar quantitative data based on the program manager survey. These data are for the 31 prototyping programs

[7]The exception is the T-46A, for which about $100 million was spent in production funds, less than that spent during development. The result is that the cost of the prototype as a proportion of procurement cost was 103 percent. This program does not meet the definitional criteria of a prototype program, and was canceled before development was complete.

Table 3.3

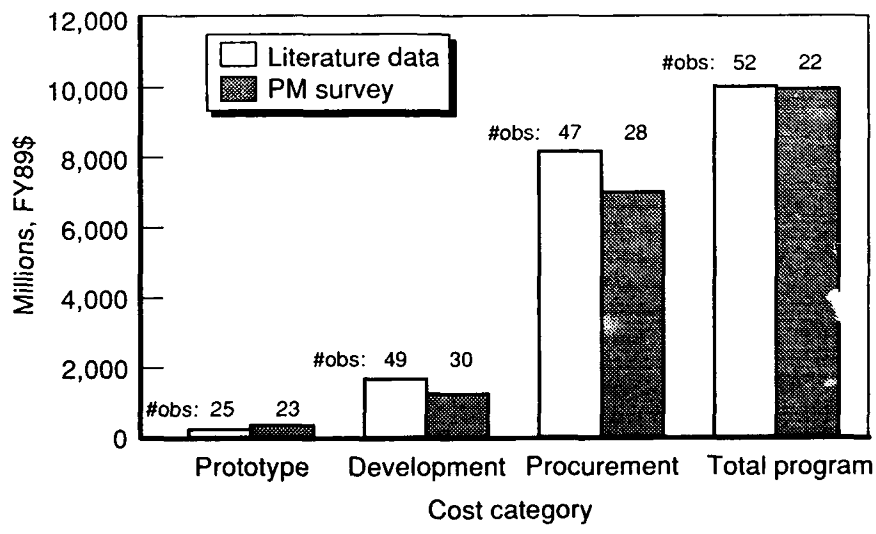
Summary Statistics for Assorted Variables (Survey Results) (prototype programs only; constant FY89$; time in months)

Variable	Unit	Obs.	Mean	Std. Dev.	Min.	Max.
No. of prototype units	number	29	21	56.2	0	302
Prototype cost	$millions	23	309.0	755.5	0	3409.1
RDT&E cost	$millions	30	1203.6	2141.5	0	11363.6
Production cost	$millions	28	7046.3	11722.3	1.3	48782.0
Total program cost	$millions	22	10079.3	15417.9	13.7	52147.8
Proto$ as % of RDT&E$		22	27.7	29.5	0	100
Proto$ as % of prod.$		22	8.6	13.6	0	49.8
Proto$ as % of total$		22	4.2	5.4	0	24.1
RDT&E$ as % of total$		22	26.3	19.6	0	90.5
Time from program initiation to:						
Milestone I	months	21	22.4	17.9	0	62
Milestone II (FSD)	months	25	52.9	30.8	0	126
Milestone IIIa (LRIP)	months	22	101.9	38.2	30	170
Milestone IIIb (full rate)	months	25	106.8	49.0	24	209
Design start	months	25	42.0	43.7	0	157
Fabrication start	months	24	47.9	42.8	2	159
First operation	months	24	64.5	46.6	6	163
Objectives achieved	months	25	79.8	53.3	10	210
Total prototype phase	months	29	43.6	28.3	8	152
Time between:						
Milestones I and II	months	21	36.4	23.1	0	79
Milestones II and IIIa	months	21	45.8	16.2	21	83
Milestones II and IIIb	months	22	61.9	22.3	20	122
Design and fabrication	months	23	8.9	7.6	0	28
Fab. and 1st operation	months	23	15.3	9.0	2	32
1st oper. and obj. ach.	months	24	13.4	11.2	1	47
Concurrency (Milestone IIIa and Obj. Ach.)	months	19	20.5	41.0	-40	86

only. Similar cost patterns emerge: prototypes tend to be a significant portion of development costs, but a fairly small percentage of total costs. Also note that while the schedule milestone averages (both decision and design) tend to follow the expected pattern, there is considerable variation about the mean. The design time variable used in the literature review is equivalent to the sum of the intervals of time between design and fabrication, and fabrication and first operation; the programs in the survey sample tended to reach first prototype operation slightly faster, on average. However, the total prototype phase times are about equal. The concurrency variable, measured here as the difference (in months) between the low rate production decision and the time at which the test phase objectives were achieved is about 20 months, indicating fairly high concurrency even in these prototyping programs.

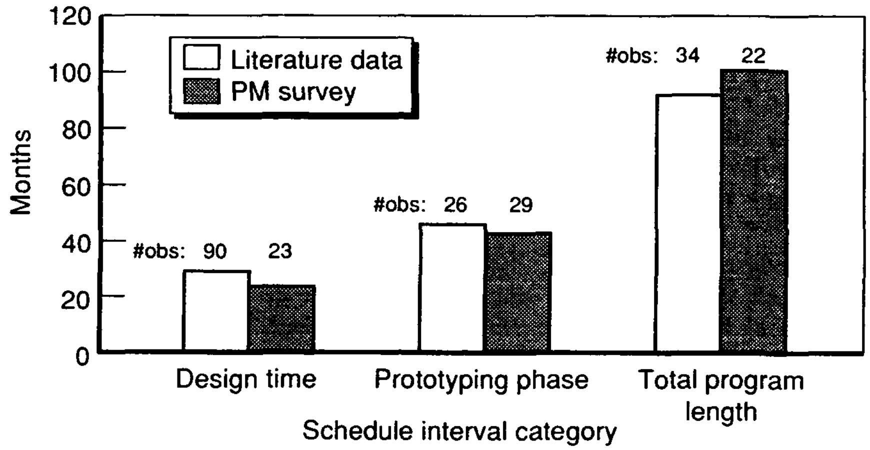
The cost and schedule data suggest that, on average, the databases are very similar, thus enhancing the generalizability of the results. Figures 3.6 and 3.7 illustrate this. The average total program cost in both the literature data and the survey are almost equal at $10 billion (FY89 constant dollars). The average cost of prototyping activities varies somewhat more: $190 million in the literature data and $309 million in the program manager survey. The differences in schedule intervals (Figure 3.7) are also relatively small. For instance, the length of the prototyping phase was 46 months in the literature database and 44 months in the survey.

One of the basic messages that emerges from Tables 3.2 and 3.3 is that there is considerable program-to-program variation across a wide range of cost and schedule variables, as indicated by the rather large standard deviations for many of these variables. This is the first indication of a basic result that will emerge in the next section: Individual programs tend to have *unique* characteristics. These individual traits result in large variances among programs along any single dimension and in large part determine the role of prototyping in a program. The use of prototyping can vary quite widely as a result.



SOURCE: Tables 3.2 and 3.3.

Figure 3.6—Comparison of Literature and Survey Cost Data (average costs in millions, constant FY 1989 dollars)



SOURCE: Tables 3.2 and 3.3.

NOTE: For survey, design time is time from design start to first prototype operation, and program length is time from Milestone I to Milestone IIIa or equivalent.

Figure 3.7—Comparison of Schedule Intervals (Literature and Survey Data)

4. ANALYSIS OF PROTOTYPING STRATEGIES

This section presents the results of an analysis of past prototyping programs using both the literature review and the program manager survey data. There are five subsections, each associated with a particular set of research questions.

The first subsection examines the range of possible prototyping strategies that have been used in the past, using the taxonomy developed in Section 2. In particular, the three basic dimensions of prototyping strategies are examined: level of integration, timing (phase in which prototyping occurred), and goals (purposes and specific objectives). Variations in the magnitude and type of risk in each program would be expected to generate a wide variation in the elements of a prototyping strategy oriented at addressing them. The results show that a wide range of prototyping strategies has been used. *Prototyping is a complex family of strategies, not one simple approach.*

We next examine the interrelationships between these three basic elements of prototyping strategies. We would expect to find some strong relationships based on the role of the prototype in the development process. Certain combinations of main purposes and specific objectives, for instance, might be associated with certain levels of system integration and timing within a program. *While there are many possible combinations of integration level, phase in which prototyping occurs, and purposes, a few combinations appear to be most common.*

The next subsection looks at whether those common strategies change across weapon system type and/or management organization. We might expect that if the level and type of risk and uncertainty and the challenges confronting a development program vary across system types, then this would be reflected by observed differences in prototyping strategies. Similarly, we might expect that each management agency would have a distinct style that would be reflected in the choice of prototyping strategies used. In fact, however, *there appear to be few identifiable differences across system types or management agency in the basic elements of prototyping strategy.*

A host of programmatic characteristics might be expected to flow from the choice of a particular prototyping strategy. Therefore, relying mostly on the program manager survey, we have also examined such items as contract type, the number of organizational layers between the program manager and the relevant higher-decision authority, and method of requirements specification to see if there are in fact strong relationships. As expected, these aspects of development programs tend to be tailored to the unique aspects of the program risk and environment in much the same way as the basic strategy elements. *Though they are subject to great variation, programmatic characteristics appear to be loosely related to the basic elements of prototyping strategies.*

Prototyping strategies might be expected to change as a result of changes in the acquisition environment. We therefore tried to identify *changes* in prototyping strategy with respect to acquisition phase, level of integration, goals, and other program and prototyping characteristics. For instance, we expected an increase in the relative frequency of subsystem prototyping as a response to increasing costs of new system developments and increased interest in upgrading existing systems. An interesting result of this analysis is that while some minor changes are identifiable, there have been no radical changes. *The basic elements of prototyping strategies have been fairly constant over time.* To the extent that past strategies were appropriate to the past acquisition environment, similar strategies might be appropriate today.

In all of the tables and graphs in this section, the absolute values of the data are much less important than the patterns and relationships they imply. As the data illustrate, the basic patterns and relationships are consistent across both the literature and survey data, and across many different aggregations of the databases. The implication is that the basic results presented in this section relating to prototyping strategies and time trends are fairly robust.

To facilitate discussion of our results, we have made a conscious effort to limit the amount of data presented in this section. Additional detail supporting the results can be found in Appendix B

RANGE OF PROTOTYPING STRATEGIES

A prototyping strategy relates the uses and values of prototypes to achievement of program goals. We have argued that the value of a prototype in weapons development is as a risk management or risk reduction tool. The various kinds of risk addressed by the prototype in large part define the purposes and objectives (e.g., goals) of the prototyping activities. These risks also define the other characteristics of a prototyping strategy: The program phase in which prototyping occurs, and the level of integration of the prototype can i ·tively be related to the type and magnitude of the risks addressed. Combinations of purposes, objectives, integration level, and program phase thus reflect prototyping strategies.[1]

This subsection examines the wide range of the basic elements that define a prototyping strategy: goals, timing, and level of integration. The importance of these elements is that they potentially have a strong influence on other characteristics of development programs. A wide range in the basic elements would indicate a wide range of prototyping strategies.

Figure 4.1 indicates that most of the systems in the literature database were prototyped at the partial system level—the platform and one or two of the basic subsystems. There are, however, a significant number of full system prototypes. The subsystem category contains mostly system upgrades, as we shall see later. Note that this category of subsystems differs in kind and context from the subsystem category in weapon type. It is fully possible that a subsystem program prototypes at the full system level (e.g., all key components of the subsystem are fully integrated).

The program manager questionnaire presents a somewhat different picture. Most of the 31 prototyping programs in the survey were prototyped at either the full system level or the subsystem level. Only 16 percent of the respondents indicated prototyping at the partial system level.

Conventional wisdom leads to the expectation that most prototyping is done at the partial system level. However, both the literature review and the survey indicate that a significant amount of prototyping is done at the full system level using articles that are apparently production representative. It is important to recognize that full system prototyping does not mean a complete, production-ready article that can be deployed to operational forces. Rather, it means a system built to scale that has integrated those subsystems critical to system success. In fact, a possible explanation for full system prototyping is that only with full system prototyping can the major integration problems be identified and resolved. Examples include the Army's Army Helicopter Improvement Program (AHIP OH-58D) and Northrop's F-20.

[1]There are obviously other associated components of a prototyping strategy. In fact, a prototyping strategy is simply a subset of a much larger set of general acquisition strategies. Other aspects of these strategies include contract type, concurrency, funding distributions over time, the number of contractors, fabrication methods, and design team size and composition, among other things. In part, the program manager survey was intended to collect some information on these other strategy elements. These data are presented in a later section.

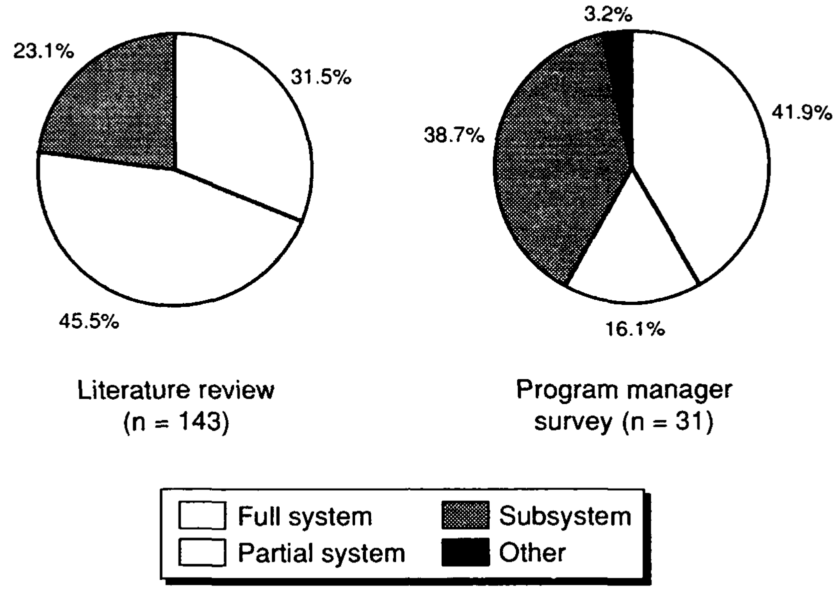


Figure 4.1—Distribution by Level of Integration

We expected that full system prototypes would occur later in a program and would be relatively more expensive (compared with partial or subsystem prototypes), with correspondingly different purposes and objectives. The next subsection examines this notion.

The program phase in which the prototyping activities occur is also important in terms of defining prototyping strategies. We would expect differences in purpose and objectives across phases. Figure 4.2 shows the distribution of prototype phases. It is interesting that FSD is dominant in both the literature and survey data at similar proportions, as one commonly held belief is that all true prototyping occurs prior to FSD. However, these data suggest that prototypes can in fact occur in any phase, the differences being a function of the purpose and objectives, and of the relative risks involved. The category "other" captures systems that are not formally programs and may not even lead to a formal program. The results on timing are consistent with both the survey and literature review results on level of integration.

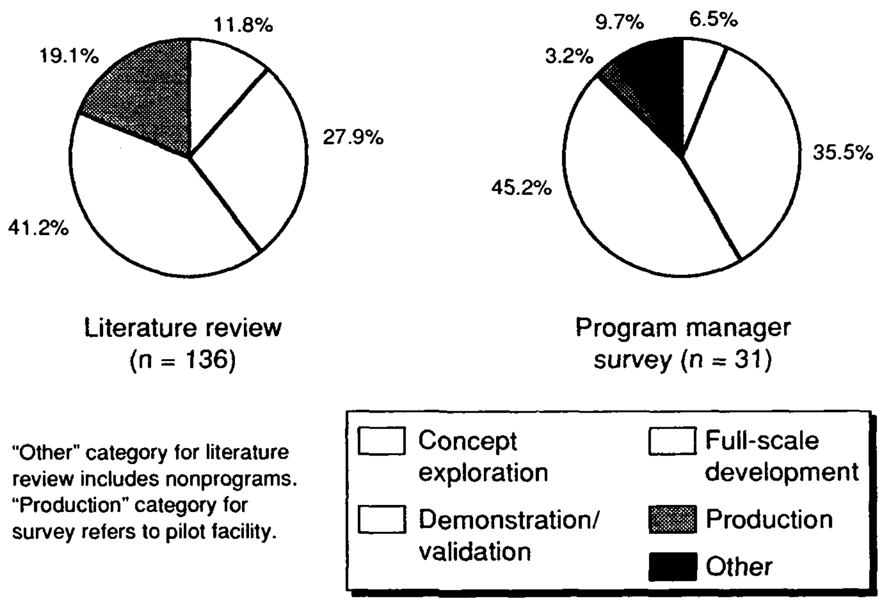


Figure 4.2—Phase in Which Prototyping Occurred

The most common purposes, both main and secondary, are dominated by technology demonstration and system design, as Figure 4.3 shows. For the literature data, a cross-tabulation of these two variables shows a strong association between them. Technology demonstration prototypes often have either technology viability or system design as secondary purposes, depending on whether the program technical risks are high or low and on the degree of maturity in the technology. System design prototypes often have technology demonstration as a secondary purpose. This combination implies a different focus than if the ordering of the two purposes were reversed. In the former case, the technology is less mature with greater technical risk; in the latter case, the technology is more mature with less technical risk associated with it. The three combinations of main and secondary purposes described above account for more than two-thirds of the total in the literature review data. These strong relationships indicate that our taxonomy does in fact help identify prototyping strategies.

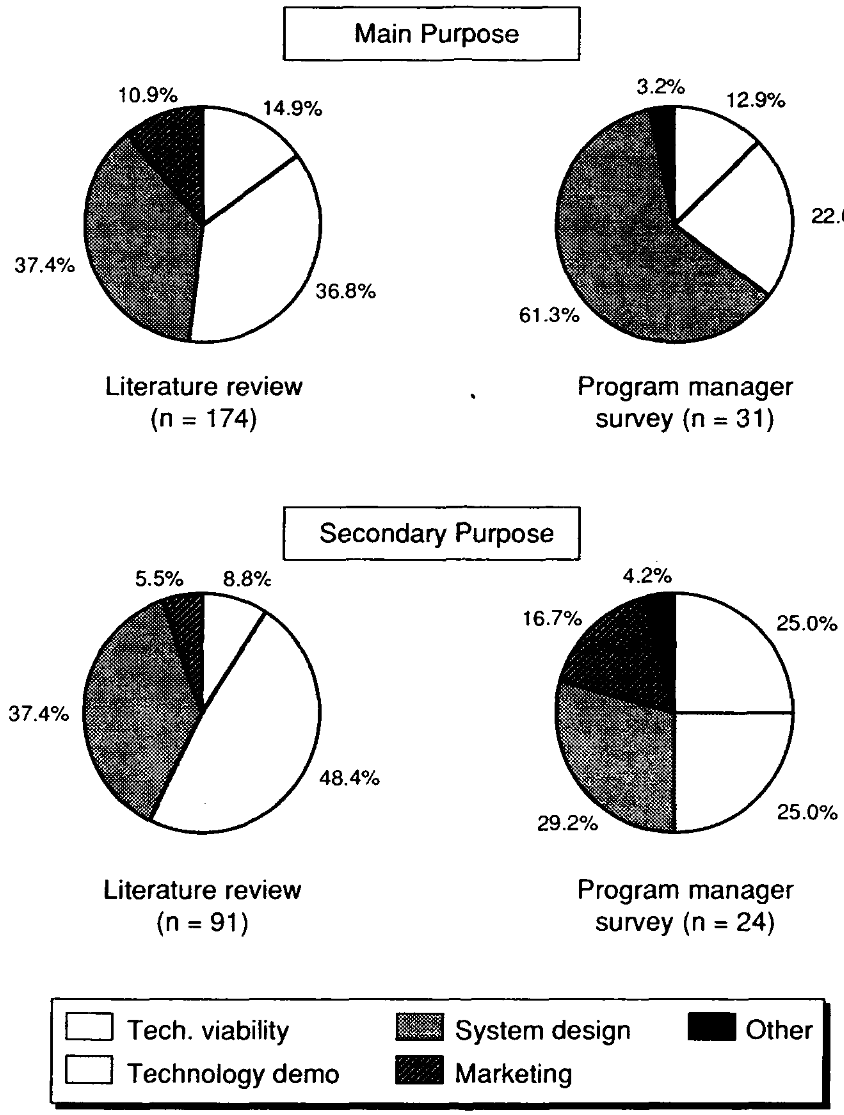


Figure 4.3—Distribution of Overall Purposes

While the proportions differ slightly, the survey results lend credence to the overall pattern and distribution of main and secondary purposes. The relationship between purposes was less clear, however. A program with a main purpose of system design had an equal number of both technology viability and technology demonstration prototypes, while programs with a main purpose of technology demonstration more often had system design as a secondary purpose. This implies that the relationships vary widely due to the unique characteristics of weapon system development programs. It is interesting that while no programs indicated marketing as a main purpose, four programs did indicate it as a secondary purpose. This is explained by the observation that the government program managers responding to the survey were less likely to consider prototypes as marketing tools than was private industry.

The frequency distributions of the three levels of specific objectives (derived from the literature) are shown in Table 4.1. Given that the objectives are scaled in order of relative importance, several interesting observations can be made. There seems to be a slight downward movement in the relative frequency of particular objectives as we move across the levels of objectives. That is, prototyping programs' principal objectives have tended to focus on the resolution of technical risks, whereas secondary objectives have often addressed developmental engineering and operational issues. The implication here is that technical risk considerations tend to be the primary focus of prototyping programs while operational considerations are of secondary importance. However, there is considerable program-to-program variation reflected in these data.

Table 4.1

Distribution of Specific Objectives[a]

	Specific Objective 1		Specific Objective 2		Specific Objective 3	
	(No.)	(%)	(No.)	(%)	(No.)	(%)
Experimental	24	14.9	0	0.0	0	0.0
Exploratory	22	13.7	20	18.2	0	0.0
Feasibility	33	20.5	26	23.6	4	7.0
Competitive	33	20.5	2	1.8	4	7.0
Developmental	10	6.2	26	23.6	11	19.3
Integration	1	0.6	9	8.2	3	5.3
Political	0	0.0	2	1.8	5	8.8
Preproduction	15	9.3	8	7.3	5	8.8
Missionized	0	0.0	12	10.9	14	24.6
Operational	1	0.6	4	3.6	7	12.3
Upgrade	22	13.7	1	0.9	4	7.0
Total	161	100.0	110	100.0	57	100.0

[a]This is an ordinal scale; specific objective 1 is defined to be more important to the program's overall goal than either objective 2 or 3, but we cannot know how much more important.

Within any given program, certain types of objectives are associated with certain other types. Common combinations include experimental and exploratory; competitive and feasibility; and, exploratory and developmental. Thus, there seem to be strong associations between particular types of specific objectives, implying that achievement of certain objectives precludes attainment of other objectives. These common combinations again suggest that prototyping strategies are highly variable and are oriented toward the specific needs and environment of a particular program.[2]

At the macro level, the basic elements of prototyping strategies—goals (purpose and objectives), timing (prototyping phase), and level of integration—have varied widely in the past. In both theory and practice, prototyping appears to be a complex family of strategies, rather than a single approach.

COMMON STRATEGIES

This subsection discusses the relationships between the basic elements that define a prototyping strategy: goals, timing, and level of integration. We believe that there are distinct relationships between these aspects of prototyping strategies, combinations of which define a particular strategy. For instance, we might intuitively believe that programs pushing the state of the art in a particular technology would have low levels of integration, occur early in a program with few prototypes, and have technology demonstration as the main purpose of the prototype phase, with perhaps feasibility and developmental-specific objectives.

These kinds of relationships are an integral part of the conceptual framework discussed previously. Under that framework, the three basic elements of a prototyping strategy are main purpose, integration level, and program phase, corresponding to the more general elements of goals, integration, and timing. We would expect that integration level would vary across purposes: Purposes corresponding to higher technical risks would have lower integration levels, while more mature technology would imply higher levels of integration. This is in fact what we find when we examine Table 4.2.[3] Programs in our database having technological risk reduction as a principal purpose have tended to prototype more at the partial system level earlier in

[2]Similar results can be observed in the program manager responses, though the numbers of programs in a particular cell are quite small. See Table B.1 for details.

[3]Table B.6 shows similar results from the survey responses.

Table 4.2

Elements of a Prototyping Strategy

	Main Purpose				
	Technology Viability	Technology Demonstration	System Design	Marketing	Total
Integration level					
Full system	0	9	24	9	42
Partial system	17	28	15	2	62
Subsystem	1	6	13	1	21
Total	18	43	52	12	125
Phase occurring					
Concept exploration	16	8	0	0	24
Demonstration/valid.	0	15	7	0	22
Full-scale develop.	1	9	30	2	42
Other (nonprogram)	5	6	3	11	25
Total	22	38	40	13	113

the acquisition process, whereas those with more of a system or marketing purpose have more frequently prototyped at the full system level later in the development cycle.

Similarly, there is a strong relationship between the phase in which the prototyping activities occur and the level of integration of the prototype article.[4] Full system prototypes are more common during full-scale development, while partial system prototyping occurs more often in pre-FSD phases, especially in the concept phase when performance requirements are being formulated.

Associations of purposes and objectives also provide a strong indication that some prototyping strategies are more common than others. As the technology matures, objectives focus less on pure technology application objectives (experimental, exploratory, feasibility), and more on demonstration of performance and military utility. The same pattern is found in the survey results.[5] In particular, programs with main purposes of technology viability and technology demonstration have few objectives at any level that involve the more mature end of the spectrum: preproduction, missionized, operational, and upgrade objectives. On the other hand, system design main purposes commonly have developmental as the first-order objective and integration

[4]See Tables B.4 and B.5 for details.

[5]See Tables B.2 and B.3 for support from the literature and survey data.

as the second-order objective. Few programs of any kind admit to having had political objectives.

While there appear to be wide variations in prototyping strategies, defined as combinations of the three basic strategy elements (goals, integration, timing), several strong relationships emerge. Partial system prototyping appears to be more often associated with technology demonstration purposes and occurs earlier in a program, while full systems are more often associated with system design purposes and occur during FSD. In fact, a few strategies seem to have been more common in past prototyping experience, at least at this aggregate level. As we will observe in a later section, however, other programmatic characteristics vary widely across these few common strategies, implying that a great deal of tailoring goes on at the detailed level.

VARIATIONS IN THE BASICS: SYSTEM TYPE AND AGENCY

This section examines whether the common prototyping strategies, and the relationships between the basic elements of prototyping strategies, vary with the type of weapon system and/or the organization responsible for funding and management.

We might expect variations in prototyping strategies across weapon types due to differences in technology, technical difficulty, or development process. In other words, some weapon types may be more commonly prototyped in certain phases, at particular levels of integration, and with certain main purposes. Table 4.3 explores some of these relationships using the literature review database.[6] For fixed-wing aircraft, there does not seem to be much difference across purposes. Helicopters, however, seem to be more commonly system design prototypes, while land vehicles are more or less equally distributed between technology demonstration and system design purposes. Missiles and subsystems are more often associated with a technology demonstration purpose. Similar patterns are observed when examining the associations of weapon type and the more detailed specific objective level.

With the experimental V/STOLs (Vertical/Short Takeoff and Landings) of the 1960s biasing the aircraft category, no real pattern emerges between weapon type and the timing of the prototyping effort, as measured by the program phase in which the prototype activ-

[6]When divided into so many categories, the program manager survey data show no dominant patterns, but they do not refute these other results. Table B.7 provides the details.

Table 4.3

Strategies by Weapon Type

	Weapon Type						
	Aircraft	Heli-copter	Land Vehicle	Missile	Sub-system	Other	Total
Main purpose							
Technology viability	18	2	1	0	4	1	26
Technology demonstration	16	6	10	17	11	4	64
System design	29	11	14	8	3	0	65
Marketing	5	1	6	4	2	1	19
Total	68	20	31	29	20	6	174
Phase occurring							
Concept exploration	17	0	5	2	3	1	28
Demonstration/validation	6	4	2	9	5	2	28
Full-scale development	28	7	5	10	6	0	56
Other (nonprogram)	8	6	3	6	2	1	26
Total	59	17	15	27	16	4	138
Integration level							
Full system	15	1	12	11	3	3	45
Partial system	38	10	9	3	3	2	65
Subsystem	13	4	1	7	6	2	33
Total	66	15	22	21	12	7	143

ities take place. There is high variability in the timing of prototyping activities across weapon types.

Integration level shows only a slightly better association with weapon type. Proportionately more aircraft and helicopters are partial systems. Land vehicles and missiles tend to be full systems, and subsystem prototypes show no significant distinction.

Table 4.3 gives the impression that prototyping strategies vary substantially across weapon types, with few suggestions of strong relationships. The implication is that any weapon type can incorporate any prototyping strategy deemed appropriate by the program's managers. There does not appear to be a dominant strategy in any category of weapon system. A more detailed breakdown examining the relationships between the elements of a prototyping strategy and particular weapon types (cross-tabulations for each system type one at a time) supports this view. The implication is that something else dominates the appropriateness of prototyping strategies. It has already been suggested that the type and nature of the risks and the relative level of system maturity fill this role. To the extent that these risks are common across weapon system types, the appropriateness of a given strategy does not vary.

We might also expect variations in prototyping strategies across management agencies, reflecting differences in management style and emphasis. The associations between management agency and the elements of a prototyping strategy are only slightly stronger than for weapon types.[7] Table 4.4 illustrates this. In terms of the main purpose of the prototype, Air Force and Army programs are evenly distributed across technology demonstration and system design purposes, while the Navy and foreign government programs seem to focus mostly on system design considerations. Joint programs between U.S. services are dominated by technology demonstration prototypes, perhaps reflecting the fact that these are mostly complicated electronics-based programs advancing the state of the art. Private ventures, both foreign and domestic, are generally marketing prototypes, reflecting the orientation of most private industry. At the more detailed specific objective level, the Air Force and the Army both have substantial proportions of competitive prototypes as a principal objective, while Navy programs are more evenly distributed. It should be noted that data availability and quality were poor for the Navy programs.

There appears to be some variation in the phase in which the prototyping activities occur. Both Air Force and Navy programs are more commonly prototyped during FSD, though a substantial number of Air Force programs are also prototyped during demonstration/validation. Army programs are the reverse of Air Force programs, with most in demonstration/validation but a substantial number in FSD. Again reflecting the private-venture nature of marketing prototypes, privately funded prototypes tend to be outside the normal program phase structure.

Integration level shows some association with management agency as well. While Air Force prototypes are well distributed across levels of integration, Navy programs have proportionately more subsystem

[7]Again, the program manager survey data do not show any dominant patterns when divided into so many cells. The exception is that Army programs appear to be more often full system prototypes with system design purposes done during FSD. See Table B.8 for details.

prototypes, reflecting the current trend toward system upgrades. Army programs, however, are balanced between full and partial systems. Again reflecting the nature of marketing prototypes, private ventures tend to be fully integrated systems.

Table 4.4 provides some slight support for the notion that prototype strategies vary across management agencies. This probably reflects differences in management style and emphasis rather than differences in prototype or weapon system characteristics. With the exception of private ventures, there is no intuitive reason why any particular prototyping strategy cannot be applied by any management agency.

It is entirely possible that the macro-level view adopted here—examining variations in prototyping goals, timing, and integration—may obscure differences in prototyping strategies across weapon system type and management agency. In theory, these differences would be more identifiable at a more detailed level of analysis and may also show up in variations in programmatic characteristics associated with the basic elements of prototyping strategies. The next section begins to examine some of these additional aspects of prototyping.[8]

VARIATIONS IN ASSOCIATED STRATEGY CHARACTERISTICS

Under the conceptual framework developed as part of this research, the three basic prototyping strategy elements—goal, timing, and integration—should in part determine a myriad of other programmatic characteristics. For instance, we might expect that main purposes would be associated with perceived or expected benefits, or that requirements specification and contract type would be associated with both the main purpose and the timing of the prototyping phase. Based mostly on the program manager survey, this subsection explores some of these relationships.

Given an identified set of risks and uncertainties associated with a particular program, we would expect that the prototyping strategy chosen would reflect the perceived benefits of prototyping. Table 4.5 shows the perceived benefits of prototyping for the 31 survey responses. These factors vary widely, corresponding with the high

[8]Unfortunately, the program manager survey data will not support a statistical analysis at that level of detail. There are too few observations in any category of weapon system or management agency to draw credible conclusions.

Table 4.4

Strategies by Management Agency

	Management Agency										
	Air Force	Navy/ MC	Army	DARPA	Joint U.S.	Other U.S.	U.S./ Foreign	Foreign (govt)	Private (U.S.)	Private (foreign)	Total
Main purpose											
Technology viability	1	0	2	0	5	1	1	2	2	0	14
Technology demonstration	14	3	17	3	13	0	2	6	4	1	63
System design	15	11	15	1	0	1	1	15	6	0	65
Marketing	0	0	0	0	0	0	0	0	14	5	19
Total	30	14	34	4	18	2	4	23	26	6	161
Phase occurring											
Concept exploration	1	0	5	2	5	0	0	3	0	0	16
Demonstration/validation	9	3	11	0	4	0	0	0	0	0	27
Full-scale development	15	14	8	0	4	0	2	11	2	0	56
Other (nonprogram)	1	0	2	1	4	0	1	1	13	2	25
Total	26	17	26	3	17	0	3	15	15	2	124
Integration level											
Full system	10	5	10	1	0	1	1	5	10	2	45
Partial system	8	2	10	2	9	0	2	13	6	1	53
Subsystem	12	9	2	1	2	0	0	4	2	0	32
Total	30	16	22	4	11	1	3	22	18	3	130

Table 4.5

Perceived Benefits of Prototyping (Survey Results)

	Main Purpose			
Benefit of Prototyping	Technology Viability	Technology Demo	System Design	Other
Prove adequacy of design	1		5	
Validate performance			4	
Validate requirement			1	
Early test, fix, test	1		2	
Reduce risk		4		
Technology demonstration	2	2	2	
Competition			1	
Provide info for trade-off		1		
Other		1	4	1

variation in prototyping strategies observed earlier. Perceived benefits range from proving the adequacy of the design and demonstrating technology to validating system performance and requirements. There is some relationship to main purpose (which is directly related to program risk under the conceptual framework), with more risk-oriented and information-generating benefits associated with technology demonstration purposes, while system design prototypes are more often associated with validation benefits. Note that there is significant agreement between the survey respondents' expectations of benefits (Table 4.5) and more general perceived prototyping benefits (Table 2.1).[9]

The survey also yielded some insight into other aspects of prototyping strategies. Conventional wisdom suggests that prototyping works best, and is in fact more common, when single point requirements are not specified in detail and when they can be modified as a result of testing. About half of the programs in the survey had requirements specified as part of the prototype contract, not much different than nonprototyping programs, with the other half incorporating more flexible contracting strategies: best effort and performance ranges and goals. Interestingly, only about half of the programs modified the requirements as a result of prototype testing; those requirements were specified in the contract.[10] Rather than substantiating conventional wisdom, the survey results suggest high variability regarding re-

[9]Unfortunately, this database cannot directly address the more important issue: whether perceived benefits were actually obtained.

[10]See Table B.11 for details.

quirement specification and the flexibility to modify those requirements.

Similarly, the actual contract types for prototyping programs show some counterintuitive results: 40 percent of the respondents indicated that the prototype phase was conducted under a fixed-price contract, a strategy that makes sense only if the contract is a best effort type. Table 4.6 shows the relationship between contract type and the way in which requirements were specified. There is a high variability, but only three of ten programs with fixed-price prototyping contracts specified requirements in the contract. The remainder were best effort or other flexible types of performance specification. As we would expect, contract types show less variability in the FSD phase, and production contracts were almost entirely fixed price.[11]

Interestingly, contract type during the prototyping phase does not seem to be strongly associated with any of the basic prototyping strategy elements. There is a wide variation in contract types across all categories of main purpose, prototyping phase, and integration level.[12] However, there is a fair correspondence between contract type in the prototyping and FSD phases: firm fixed-price and cost plus incentive prototype contracts tend to be associated with similar contract types during FSD.[13]

Other aspects of prototyping strategies show some variations and relationships across program phases. Table 4.7 suggests that while

Table 4.6

Contracting and Requirements Specification: Prototyping Phase

	Type of Contract					
Form of Requirement	FFP	CPI	CPIw/c	CPFF	Other	Total
Contract specific	3	4	1	1	3	12
Performance goal	2	2	2	1	0	7
Performance range	1	0	0	1	0	2
Best effort	2	0	0	0	0	2
Other	2	0	0	0	0	2
Total	10	6	3	3	3	25

NOTES: FFP = firm fixed price; CPI = cost plus incentive; CPIw/c = cost plus incentive w/ceiling; CPFF = cost plus fixed fee.

[11]See Table B.10 for details.

[12]See Table B.12.

[13]See Table B.9.

Table 4.7

Nature of Technical Advance and Timing

	Prototyping Phase				
	Concept Explor.	Dem./Val.	FSD	Production	Other
Technical advance					
Evolutionary	1	7	12	1	1
Revolutionary	1	4	2		2
When planned					
Before	2	9	11		2
After		2	2	1	1

n = 32 for Technical advance; n = 30 for When planned.

most programs consider themselves to be evolutionary in nature, the revolutionary programs more often are prototyped earlier in a development program. Given the nature of the risks involved, that outcome is what we would expect: Higher risk programs are prototyped sooner, most often to demonstrate technical feasibility. It is also interesting that most prototype programs are planned to include prototyping from the outset, which seems to be a more efficient acquisition strategy than making changes to an ongoing development program. The hierarchical level of the official who makes the decision to prototype was equally distributed across the spectrum from the USD(A) level to the program manager. On average, there were two organizational decisionmaking layers between the program manager and the top decision maker for the prototype, FSD, and production phases.

Though we might expect that the number of prototypes fabricated and tested would be related to the elements of prototyping strategy, this analysis finds no evidence in support of this notion. Most programs had relatively few prototypes, with no apparent relationship with purpose, integration level, or phase: 68 percent of the programs from the literature review data have five or less prototypes, relatively evenly distributed across main purposes and integration levels. The number of prototypes might instead be related to the cost or time available for prototyping activities. That notion is explored in a later section.

Consistent with the observation that prototyping strategies vary widely, programmatic characteristics also vary widely. In many cases, aspects of programs such as contract type, the way in which requirements are specified, and relative technological advance appear to be related not only to the goals, timing, and integration dimensions of prototyping strategies, but also to each other.

An interesting question that arises at this point is whether prototyping strategies determine programmatic characteristics or whether those characteristics determine that strategy. Our conceptual framework hypothesizes that the programmatic characteristics flow from the basic strategy elements, but this cannot be proved definitively; a credible argument can be made for either relationship. The evidence presented in this section suggests only that there is some strong interaction.

PROTOTYPING STRATEGIES OVER TIME

We have already seen that both the literature review and program manager survey databases used in this analysis are somewhat biased because data were more readily available on more programs in more recent years (see Figures 3.4 and 3.5). Recognizing that there could have been more prototype programs in earlier years, we can still look for trends in the data.

The basic question is whether the nature of prototyping has changed over time. We approached this by examining the trends in the basic elements that comprise prototyping strategies. Table 4.8 shows the main purposes of prototyping activities by five-year periods based on the year the program started. The bias mentioned earlier is reflected in the last column. The data show that technology viability was the most frequent purpose prior to 1965, while technology demonstration and system design purposes were more common in later years. Notice

Table 4.8

Changes in Prototyping Purpose over Time

	Main Purpose				
Time Period	Technology Viability	Technology Demonstrator	System Design	Marketing	Total
1955–59	3	2	0	0	5
1960–64	8	2	6	1	17
1965–69	2	3	7	1	13
1970–74	1	12	9	0	22
1975–79	1	4	8	2	15
1980–84	3	13	12	7	35
1985+	2	6	7	2	17
Total	20	42	49	13	124

also that there were substantially more marketing prototypes, mostly private ventures, in the early 1980s. While admittedly biased toward more recent programs, the data do provide some slight evidence that the main purposes of prototypes have changed somewhat, leaning toward proof of performance and operational utility and away from demonstrations of technological feasibility. A similar pattern emerges in the specific objectives.[14]

Table 4.9 shows a fairly strong trend with respect to the program phase in which prototyping activities occur. Earlier periods appear to have had more concept exploration prototypes, while in the early 1970s, there were more prototypes occurring in demonstration/validation. That result is consistent with the trends in main purpose: technology viability/concept exploration phase and technology demonstration/demonstration phase combinations are some of the more common strategies. Further, the trend in the timing of prototyping activities may be a result of Deputy Secretary Packard's push for "advanced development" prototypes in the early 1970s. The acquisition programs of the late 1970s and early 1980s had more prototyping during the FSD phase. Reasons for these patterns might include the recent trend toward upgrading, which is often an FSD effort, or use of more mature technology in recent systems. It is also noteworthy that there were more prototypes outside of the normal service programs in more recent years. These are the marketing prototypes that we saw in Table 4.8. The trend in marketing prototypes

Table 4.9

Trends in Phase When Prototyping Occurred

	Acquisition Phase				
Time Period	Concept Exploration	Demonstration/ Validation	Full-Scale Development	Other (Nonprogram)	Total
1955–59	2	1	2	1	6
1960–64	8	0	7	0	15
1965–69	2	3	7	2	14
1970–74	2	13	4	2	21
1975–79	0	3	10	3	16
1980–84	3	4	17	7	31
1985+	2	1	3	2	8
Total	19	25	50	17	111

[14]The survey data, covering the period 1970 through 1989, provide no evidence of a change in main purposes over time. There appears to be no significant difference between pre- and post-1980 programs. See Table B.15.

can perhaps be explained by the encouragement of private investment in weapon system development in recent years.[15]

Examination of Table 4.10 reveals no real pattern in integration level over time. Though it appears that fully integrated prototypes are more common in recent years, this contradicts conventional wisdom that prototyping costs have been increasing. Full system prototyping is obviously more expensive than either partial system or subsystem prototyping. However, it is consistent with the notion that system integration is becoming a major technical challenge in weapon system development. Full system prototypes are needed to resolve many integration risks. It is interesting that the frequency of subsystem prototyping has remained relatively constant over time. Given the increasing costs of systems, the fact that much of this increase is due to incorporation of greater amounts of more complex electronics, and the trend toward integration of all these electronics as one of the major technical challenges in weapons development, we might have expected to see an increasing trend in subsystem prototyping. The cyclical pattern of partial systems remains unexplained.[16]

The program manager survey data allowed an analysis of trends in some of the programmatic characteristics associated with prototyping strategies. Results indicate no identifiable change over time in contract types, requirements specification, decision making, etc. In part, the large variation in the data and the few observations in any particular grouping explain this result.

Table 4.10

Trends in Integration Level of Prototypes

	Integration Level			
Time Period	Full System	Partial System	Subsystem	Total
1955–59	2	4	0	6
1960–64	4	12	0	16
1965–69	1	6	4	11
1970–74	3	12	5	20
1975–79	6	4	5	15
1980–84	10	12	5	27
1985+	5	6	2	13
Total	31	56	21	108

[15]Table B.16 supports these trends using the program manager survey data.

[16]Table B.17 shows some slightly different results from the survey. Subsystem prototypes are considerably more common in more recent years for this sample of programs, while full system prototypes have decreased in frequency.

5. PROTOTYPING AND PROGRAM OUTCOMES

Prototyping is thought to be valuable as an acquisition strategy because it can potentially contribute to good program outcomes, as measured by cost, schedule, and performance. If a prototyping strategy successfully reduces program risks, then cost, schedule, and performance outcomes should be improved. In attempting to demonstrate this contribution, however, we encountered several problems.

One fundamental problem is that while we can examine prototyping programs, or compare the outcomes of prototyping and nonprototyping programs, the outcome for the same program with and without prototyping can never be known. In other words, we can only hypothesize about the difference in outcome for a program in which prototyping was considered as a strategy and rejected. There is a related problem of confounding variables. Many factors affect program cost, schedule, and performance outcomes, and it is not often possible to separate these effects from each other. Hence, we can never definitively know the relative contribution of prototyping to program outcomes. Additionally, whether or not we should expect prototyping to improve cost, schedule, and performance outcomes (e.g., whether baseline estimates under prototyping will more accurately reflect actual outcomes) is a function of both the timing of information availability resulting from prototyping activities and the willingness of decision makers to incorporate that information in establishing or attempting to meet those baselines.

An important conceptual problem is that cost, schedule and performance outcomes do not measure what we are really interested in: the cost-effectiveness of a system in operational use. Unfortunately, we cannot measure the effectiveness of a system in operational use, or the cost-effectiveness of an acquisition strategy or program in delivering that system for use, in a meaningful way. Thus, we are left with examining cost, schedule, and performance outcomes as the only reasonably objective measures of program "success" available.

The observed effect of prototyping activities on program outcomes might look either of two ways. First, information gained through early prototyping can be used to improve the accuracy of our baseline estimates of cost, schedule, and performance.[1] We would expect that

[1]These three baselines are generally established at the Milestone I, II, and IIIa decision points in the development process.

the information generated through prototyping activities would reduce program risk by allowing managers to anticipate and plan for technical problems. Thus, a prototyping program should incur lower cost growth and schedule slip as compared to nonprototyping programs, assuming that this information was used in determining the program cost and schedule baselines against which such outcomes are measured.

Second, the effect of prototyping may look different if the information generated is not used in formulating program baselines, however. For instance, one type of successful prototyping activity would uncover previously unidentified technical problems affecting estimates of cost, schedule, and performance. In fact, this is arguably one of the more important functions of prototyping, since it directly addresses risk in the program. From a programmatic perspective, however, we might observe the result as cost growth and/or schedule slip measured from a baseline that does not include the information generated through prototyping; hence, we really cannot tell whether greater or lesser cost growth and schedule slip should be associated with prototyping. If the cost and schedule growth was measured from a baseline calculated *prior* to the prototyping activity, then growth would be expected. If the baselines were determined *after* the prototyping activities, then we might expect lower growth. It is the timing and use of information generated during prototyping activities that is the basis of the effect of prototyping on program outcomes.

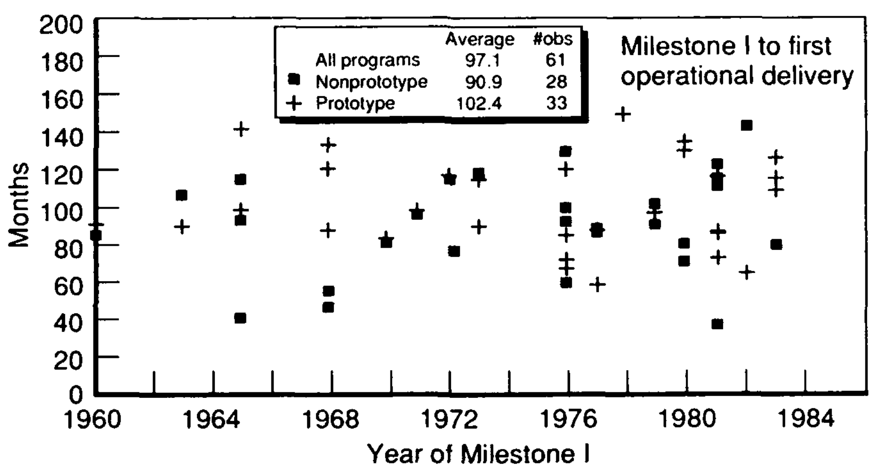
Given the difficulties involved, it is not a surprise that the evidence linking prototyping and program outcomes is fairly weak: *the effect of prototyping on program outcomes is ambiguous due to confounding variables.* In general we do not know enough about the specific information generated and how it was used to establish a relationship between prototyping and program outcomes and identify a fundamental difference between prototyping and nonprototyping program outcomes. Thus, the results presented here may reflect the limitations of the analysis rather than any relationship between prototyping and program outcomes. Large sample studies cannot control for all the factors that might affect outcomes. However, case study approaches have been more successful in gaining insight into the value of prototyping for specific programs.[2] Nonetheless, available data from this

[2]See G. K. Smith et al., *The Use of Prototypes in Weapon System Development*, RAND, R-2345-AF, March 1981, and Mark A. Lorell and D. Hoffman, *The Use of Prototypes in Selected Foreign Fighter Aircraft Development Programs*, RAND, R-3687-P&L, September 1989.

and other RAND research do offer some insight into the relationship between prototyping and program outcomes.

PROTOTYPING, PROGRAM DURATIONS, AND SCHEDULE SLIP

Proponents of prototyping believe that prototyping does not increase actual program duration, while opponents believe that it does. If prototyping had no net effect on program duration, then we might expect to find slightly longer plans, on average, in anticipation of future slip, but similar actual program durations. Figure 5.1 shows the actual program duration for 61 aerospace programs, measured as the time from program start (Milestone I or equivalent) to first operational delivery. Programs meeting the narrow definition of prototyping are shown. Several interesting observations can be drawn. First, there is a high degree of variation in actual program durations, both over time, between prototyping and nonprototyping programs, and within these categories. Second, prototyping programs do appear to take approximately 12 months longer to reach first operational delivery (significant at the 10 percent level). Table 5.1 provides some additional detail supporting this. Planned program durations are in fact slightly longer in prototyping programs than in nonprototyping programs (as expected), but subsequent schedule slip is also greater,



SOURCE: *Selected Acquisition Reports* as of December 1988.

NOTE: T-test of difference between means indicates that mean for prototypes is different from nonprototypes at the 10 percent significance level.

Figure 5.1—Prototyping and Actual Program Duration

Table 5.1

Duration and Slip Differences Between Prototyping and Nonprototyping Programs (measured in months from Milestone I to first operational delivery)

	Prototyping	Nonprototyping	All programs
Planned length	88.4	81.0	85.3
Pre-FSD slip	2.7	-0.44	1.3
Slip in FSD	12.3	5.1	9.1
Total program slip	13.7	6.2	9.8
Actual duration	102.4	91.0	97.1

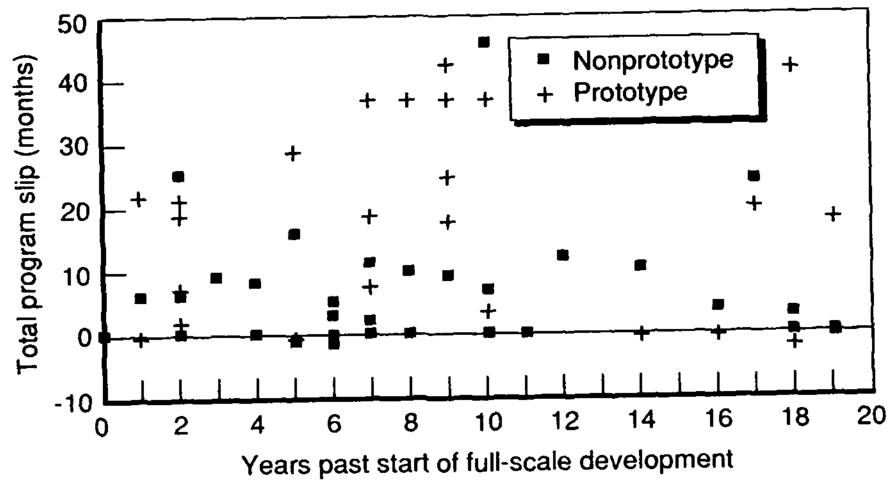
SOURCE: Data derived from *Selected Acquisition Reports* through December 1988.

on average. Hence, prototyping programs tend to have slightly longer actual program durations than nonprototyping programs. Again, care is required in interpreting this result. It may be that the schedule slip experienced in prototyping programs reflects a successful prototyping activity; problems were identified and time was taken to resolve them, thus improving the quality of the first operational unit delivered.

A recent study examining factors affecting acquisition program duration provides inconclusive evidence that prototyping is related to either program length or schedule slip.[3] Of the ten programs examined in some detail, eight contained distinct prototyping phases. The variation in both the planned and actual time from program start to first operational delivery is high. Similarly, the schedule slip experienced by these programs is highly variable, ranging from 0 to about 80 percent of the original plans.

A broader view of the relationship between prototyping and schedule outcomes is provided by Figure 5.2, which shows the schedule slip (measured as the slip in first operational delivery) for prototyping and nonprototyping programs. The data indicate that on average, prototyping programs incur more slip in first delivery (see Table 5.1): 13.7 months versus 6.2 months for prototyping and nonprototyping programs respectively. However, there is considerable program-to-program variation. Again, this result is not as counterintuitive as it first appears. Prototyping may result in identification of technical

[3]Jeffrey A. Drezner and Giles K. Smith, *An Analysis of Weapon System Acquisition Schedules*, RAND, R-3937-ACQ, December, 1990.



SOURCE: *Selected Acquisition Reports* as of December 1988.

NOTE: Slip measured as deviation in first operational delivery.

Figure 5.2—Prototyping and Schedule Slip

deficiencies earlier in a program, thus causing schedule slip while actually improving overall project outcome. Nonprototyping programs might not uncover the same problem until well into the production phase. There is currently no database available that would allow definitive testing of this notion.

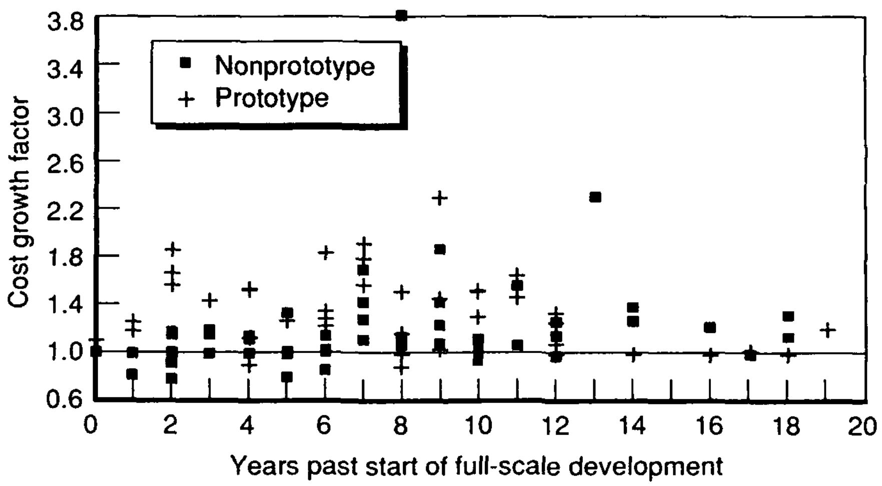
PROTOTYPING AND COST GROWTH

As with schedule slip, cost growth depends on when the results of prototyping are used in managing the program. If a cost baseline was established using the information generated by prototyping, we would expect improved cost estimation accuracy, thus reducing cost growth as measured from the baseline estimate. If that baseline was established either prior to the prototyping activities, or without using information available through prototyping activities, then prototyping activities that generated information resulting in increased cost estimates would be expected to increase cost growth measured from that baseline. Figure 5.3 shows the total program acquisition cost growth of prototyping and nonprototyping programs.[4] The distribution again

[4]Cost growth is measured as the difference between a baseline estimate and the most current estimate or actual program costs, after correcting for inflation and

shows a high variation in cost growth outcomes between prototyping and nonprototyping programs for any level of program maturity (measured as years past FSD start). The dollar-weighted average[5] cost-growth ratio for the prototyping programs in Figure 5.3 is 1.30, while nonprototyping programs average 1.16, a fairly large difference.[6]

A similar rationale suggests that prototyping would have a greater benefit earlier in a program rather than later because information allowing improved estimates is made available earlier. However, only a slight difference was found between the cost growth of programs that prototyped prior to FSD (1.30) and after FSD start (1.34).



SOURCE: Raw data from *Selected Acquisition Reports* as of December 1988.

Figure 5.3—Prototyping and Cost Growth (Development Estimate Baseline)

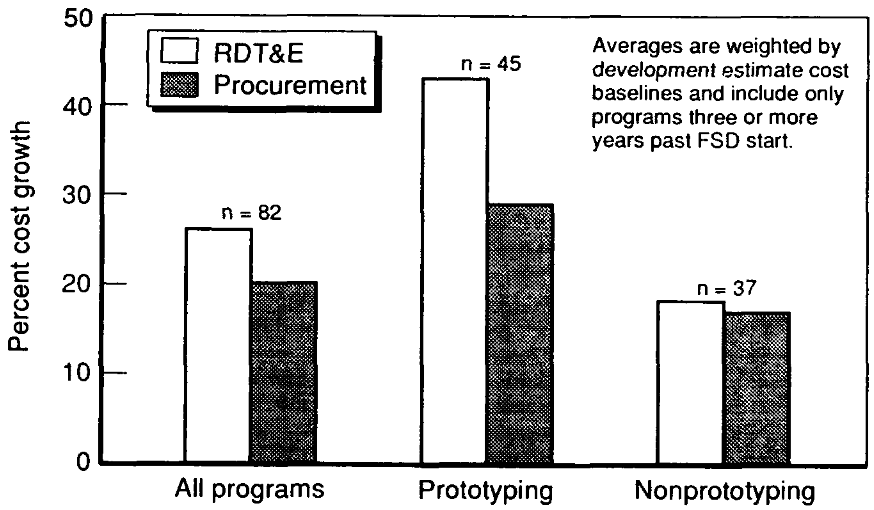
---

quantity changes. A factor greater than one indicates cost growth. These data, derived from *Selected Acquisition Reports*, are based on ongoing work by the author.

[5]Total program cost at the time of the development estimate is used as the program weight in these calculations. All cost growth figures are referenced to the development estimate baseline.

[6]These figures include all programs for which it was possible to classify prototyping vs. nonprototyping. A subset of this database—programs in which the prototyping vs. nonprototyping distinction can be made with higher confidence—shows similar results, though of smaller magnitude. For the high confidence subset, prototyping programs had a dollar-weighted average cost-growth factor of 1.26, and nonprototyping programs had 1.19.

We can also examine the cost growth associated with the research, development, test and evaluation (RDT&E), or procurement accounts for these programs separately. We might expect to observe relatively higher R&D cost growth and lower production cost growth in prototyping programs, indicating identification and mitigation of problems prior to production. Nonprototyping programs should incur relatively higher cost growth in the procurement account, while prototyping programs should incur higher RDT&E cost growth. Figure 5.4 shows this comparison. For nonprototyping programs, the dollar-weighted average cost growth ratio for RDT&E is 1.18, while prototyping programs averaged 1.43, a significant difference in the expected direction. The production phase averages are 1.17 and 1.29 for nonprototyping and prototyping programs, respectively. These results do not provide evidence to support the hypothesis that prototyping increases R&D cost growth and reduces procurement cost growth.[7]



SOURCE: Raw data from *Selected Acquisition Reports* as of December 1988.

Figure 5.4—Comparison of RDT&E and Procurement Cost Growth (Prototyping and Nonprototyping Programs)

[7]Again, for the high confidence subset of the database, results are similar, as the table below shows:

		RDT&E	Procurement
All programs	(n = 52)	1.32	1.20
Prototyping	(n = 29)	1.36	1.23
Nonprototyping	(n = 23)	1.29	1.19

Table 5.2 presents a comparison of dollar-weighted average cost growth for prototyping and nonprototyping programs by weapon system type. Both development and procurement cost growth are shown, as well as cost growth for the total program. The table demonstrates considerable variability in all three measures of cost growth across weapon types. We need to use caution when interpreting the data in the table, however, because of the small number of observations in each category. For instance, while total program cost growth for aircraft averages 18 percent for programs that included prototyping activities and 27 percent for nonprototyping programs, the result is entirely dominated by a single program: the F-111. The F-111 is a large program with a high cost-growth factor, so it tends to dominate

Table 5.2

Cost Growth by Weapon Type: Prototyping vs. Nonprototyping

	Development		Procurement		Total Program	
	Proto. (# obs.)	Nonproto. (# obs.)	Proto. (# obs.)	Nonproto. (# obs.)	Proto. (# obs.)	Nonproto. (# obs.)
All programs	1.43 (45)	1.18 (37)	1.28 (45)	1.17 (37)	1.30 (44)	1.16 (46)
Aircraft	1.40 (5)	1.31 (9)	1.13 (5)	1.26 (9)	1.18	1.27
Missile	1.47 (22)	1.02 (8)	1.31 (22)	1.07 (8)	1.35	1.05
Helicopter	1.35 (4)	n/a	1.39 (4)	n/a	1.39	n/a
Electronic	1.39 (6)	1.23 (10)	1.39 (6)	1.12 (10)	1.32	1.16
Munition	1.28 (5)	n/a	1.19 (5)	n/a	1.20	n/a
Vehicle	2.15 (2)	n/a	1.60 (2)	n/a	1.70	n/a
Ship	n/a	1.19 (8)	n/a	1.07 (8)	n/a	1.06
Space	.99 (1)	1.34 (2)	1.13 (1)	1.10 (2)	1.05	1.22
Other	n/a	n/a	n/a	n/a	n/a	n/a

SOURCE: Raw data from *Selected Acquisition Reports* as of December 1988. Analysis from ongoing work by author.

NOTE: Data are dollar-weighted averages for programs three or more years past FSD start measured from the development estimate baseline.

a dollar-weighted calculation. Removing the F-111 results in a 13 percent cost-growth average, a significant reduction and a change in the relative magnitudes of average cost growth for aircraft systems.

Table 5.2 points to some interesting issues that need to be more fully explored. For instance, the database seems to suggest that all helicopter and munition systems are prototyped while no ships are. Though we might suspect that ships are not amenable to prototyping, it seems unlikely that there is something in the technical nature of helicopters and munitions that would require prototyping. Hence, this result should not be taken as definitive without further research. Similarly, it appears that significant cost-growth differences between prototyping and nonprototyping programs appear in missile and electronic systems, with prototyping programs incurring higher development and procurement cost growth. The current database does not support a detailed explanation of this apparent phenomena.

SUMMARY

The evidence linking prototyping with program outcomes is fairly weak. In most cases, cost and schedule outcomes vary widely, with no demonstrated relationship between prototyping and outcome. Most of the differences between prototyping and nonprototyping programs were not significant from a statistical standpoint. It might be, for instance, that only the more technically challenging programs include prototyping activities, in which case we might expect higher risk even after prototyping. In short, we do not know enough about the factors affecting program outcomes to know whether prototyping has an effect. The likelihood is that many other factors dominate any effect of prototyping on program outcomes. Such factors as budget stability, technical difficulty, and perhaps the ability and willingness of decision makers and program managers to use improved information in cost and schedule estimates are likely to dominate any comparison of prototyping and nonprototyping programs.

An interesting hypothesis that deserves attention in future research is the notion that choosing an appropriate prototyping strategy may make the difference between positive and negative outcomes for a given program. Unfortunately, this again raises the problem described at the beginning of this section: We cannot know what the outcome of a prototyping program would have been if it was not prototyped; we can only speculate. Further, the currently available data do not support an analysis of the appropriateness of a particular prototyping strategy for a particular program.

6. OBSERVATIONS ON PROTOTYPING POLICY

SUMMARY OF FINDINGS

The basic results of this analysis of the nature and role of prototyping in weapon system development can be summarized as follows:

- Prototyping is a complex family of strategies, with evidence of wide variation in past use. There is no single generic approach to prototyping that is universally applicable.
- A few prototyping strategies (combinations of three basic elements: goals, timing, and level of integration) appear to be most common.
- There are few identifiable differences in prototyping strategy between services or across weapon types.
- Detailed programmatic characteristics, such as contract type, requirements specification, number of prototypes, decision layers, and amount of documentation, are loosely associated with the basic strategy elements and tend to flow from the choice of those elements.
- Macro-level strategies have been fairly constant over time, though some factors may have changed at the detailed level.
- The effect of prototyping on program cost, schedule, and performance outcomes is ambiguous due to the effect of confounding variables.

This section goes beyond these results and begins to address the more normative issue of what the characteristics of prototyping policy should be. While it draws on, and is informed by, these findings, it adds other arguments that are not necessarily demonstrated by the analysis presented earlier. Hence, this section should be viewed as a more subjective and qualitative treatment of prototyping issues, somewhat divorced from the analysis just presented. It addresses the elusive normative goal of formulating useful prototyping policy.

PROBLEMS AND PROSPECTS FOR FIRM CRITERIA

Policy makers have often sought criteria to help set effective and unambiguous policy on when prototyping should be used in the course of weapon system development and what kind of activities prototyping should entail. Though many attempts have been made to develop such criteria, they have met with little success. The research just presented suggests one possible reason: the lack of an unambiguous, agreed-on definition of what a prototype is. In other words, lack of a generally accepted definition of prototyping, including potential benefits, makes consistent policy formulation and implementation difficult. Thus, there remains a lack of consistent guidance for policy and practice on the use of prototyping.

We offer a broad definition:

> A prototype is a tangible product (hardware and/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 not necessarily a complete system, but rather focuses on those high-risk areas critical to system success.

The key for policy guidance, however, is that a prototype is intended to generate information to improve the quality of decisions in an environment of risk and uncertainty, not merely to demonstrate satisfaction of contractual performance specifications. Hence, a successful prototype program may lead to cancellation of a proposed system, a reduction in its level of technological advance, or continuation of development as planned.

Though we have intentionally defined prototypes in the broadest possible manner, one important aspect needs clarification: the timing of the prototyping phase within the acquisition process. We argue that prototyping can, and does, occur both before and after Milestone II. Full-scale (but not necessarily full system) prototyping usually occurs before the start of engineering and manufacturing development (EMD), as in the classic case of the Light Weight Fighter program (YF-16/17) or the recently completed ATF demonstration validation phase. Subsystem level prototyping, while not "full scale" in the same sense, can and does occur both before and after beginning EMD. That distinction is important to our basic policy recommendations.

Our analysis of past prototyping experience has documented the wide range of uses prototypes have in weapon system development. That extreme variation in prototyping strategies is expressed at the highest level in terms of the goals of the prototyping activities, the timing of those activities with respect to the overall program schedule, and the level of system integration of the prototype(s). While there are different ways to use prototyping, all are intended to reduce risk and uncertainty of one sort or another. Our systematic analysis of prototyping confirms what many in the acquisition field have learned case by case: that risk and uncertainty—and thus information needs—vary dramatically from program to program. That variation hinders development of specific prototyping criteria that can be universally applied.

Theoretically, when deciding whether or not to prototype, one would compare the costs of prototyping in a particular program with its benefits. Figure 6.1 illustrates this deceptively simple concept. We will only want to prototype when the benefits of prototyping are greater than or equal to the costs. Hence, for any point above the 45 degree line in Figure 6.1, we would prototype; for any point below it, we would not. Unfortunately, this conceptual decision framework is not simple to put in practice. In particular, both costs and benefits are multidimensional.

There are several ways in which costs can (and should) be considered. The obvious is in terms of dollars, both the actual expenditure involved in the prototyping activities and as the percentage of total program acquisition costs. But there are additional costs to be considered. Time is a form of cost, for example, though it may not be measured in dollars. There are political costs as well. For instance, taking the time to demonstrate technology might give opponents of a

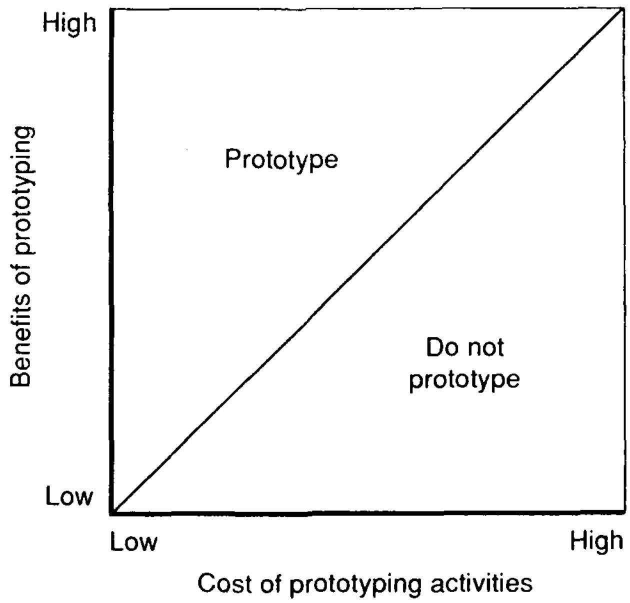


Figure 6.1—Notional Criteria for Prototyping Decisions

program time to gather support to terminate or restructure it. Similarly, a prototyping activity that demonstrates that a technology is not mature enough to be incorporated in a new system might also provide a basis for increased political opposition to the entire project, even if the relative level of technological advance of the system was reduced as a result of information gained through prototyping.

Benefits are perhaps even more difficult. For instance, benefits may be thought of as a reduction in development risks. But we cannot quantify how much risk is reduced. Nor can we know exactly what kinds of risks are reduced for each type of prototyping activity. Risks might be stated as the cost consequences of proceeding into the next program phase with a poor design. That has two components: the costs of an undesired event happening because of the poor design, and the probability that the event will occur. Both components are highly uncertain. There are other benefits to prototyping as well, such as the possibility that more accurate cost, schedule, and performance estimates will allow better-quality decisions regarding cost, schedule, and performance trade-offs, and increase design options.

In summary, there are tremendous difficulties involved in operationalizing the simple concept depicted in Figure 6.1. We cannot be confident that we can identify all possible benefits and costs. Each benefit and cost is measured on a different scale, if it can be measured at all, and we do not know how to reconcile those scales consistently across all the dimensions of costs and benefits. Even if we could measure all relevant costs and benefits, we do not know how to consistently weigh them in a decision process. Differences in program characteristics (e.g., technological difficulty and maturity, cost and schedule constraints, the level of uncertainty regarding the technology's military utility, etc.) suggest that those weights will differ greatly across programs and also as a function of the goals and activities involved in a particular prototyping application.

TOWARD MORE FLEXIBLE POLICY GUIDANCE

Nonetheless, several general principles seem valid in prototyping policy. The basic policy guideline might be to assess the extent to which prototyping is both useful and appropriate in a particular case. One fundamental consideration is the trade-off between the net benefits (benefits minus costs across all relevant dimensions) of prototyping and the type and magnitude of risk in a development effort, as illustrated in the discussion of Figure 6.1. Table 6.1 lists just a few of the factors that need to be carefully evaluated in assessing that trade-off; it is certainly not meant to be exhaustive. Hence, prototyping policy

Table 6.1

Factors to Consider in Making Prototyping Decisions

Benefits from Prototyping
• Reduces technological risk and uncertainty
• Identifies critical system integration issues
• Permits more accurate cost, schedule, and performance estimates
• Reduces cost consequences of proceeding into subsequent phases with poor design
• Allows necessary design changes to be identified early
Costs of Prototyping
• Increased front end cost
• Prototyping phase cost as percent of total program cost
• Longer front-end time (interval for prototyping phase)

might require the evaluation and balancing of the relative technological advance in a system, uncertainty regarding the utility of a new concept, and the maturity of the technology being incorporated, given cost and schedule constraints. Unfortunately, there is no way to consistently measure those dimensions. Further, even if we could accurately measure the relative technological maturity of a system design, for instance, we still do not know how much weight to give any single factor in the overall decision calculus. The policy guidance we are suggesting is that these and other similar factors be explicitly included in the decision process when a program's acquisition strategy is being formulated. We are not specifying exactly which factors are important or how they should enter the decision process. In the end, there is no substitute for informed judgment made by experienced managers and engineers.

The decision process we have in mind here can be illustrated (rather simplistically) with a brief example. The Advanced Medium Range Air-to-Air Missile (AMRAAM) program presents a classic case of when prototyping should have been done and in fact was done.[1] AMRAAM incorporated significant technological advance, with the associated risk; it was a large program in terms of both quantity and cost, and full-scale prototyping could be performed in a competitive environment with articles built on soft tooling. In contrast, the B-2 program is a case in which the large unit cost, small production quantity, and technical challenge and cost of fabricating even development items (full production tooling is required) makes full-scale prototyping

[1]This evaluation is independent of the observed cost and schedule growth in the program, which may in part be attributed to failure to completely incorporate the information generated by the prototyping phase into structuring later phases.

unattractive. Nonetheless, subsystem and component-level prototyping could still be done, and was.

How can we determine the dividing line between situations that do and do not justify prototyping? Our research on prototyping has not produced unambiguous analytical results. However, during the course of our research on this and related topics, we have concluded that some form of prototyping is almost always appropriate. This is basically because there are powerful institutional pressures that lead to systematic underestimation of program risks. We believe that the policy should be to use some form of prototyping in almost every case, and the burden of proof should be on those who argue that a prototyping activity is unnecessary or impractical. In cases where full-scale articles are too expensive or technically impractical, subsystem prototyping (e.g., avionics test beds) might still be appropriate. While less than full-scale prototyping may not capture the complete set of benefits attributable to prototyping (e.g., system integration risk cannot be adequately addressed), it still offers a net benefit to the program.

This conceptual framework for policy and decision making is quite similar to what is contained in existing regulations. DoD Instruction 5000.2 mandates competitive prototyping for all major weapon systems, in accordance with law.[2] The regulation states that requirements for prototyping (e.g., a prototyping strategy in our terminology here) will be established at the Milestone I decision point based on a program-specific risk assessment. The regulation even allows for prototyping activities during FSD/EMD, a contentious point in the past. Further, the Under Secretary of Defense for Acquisition, Donald Yockey, has delineated criteria in a fashion paralleling that presented here:

> We require the use of competitive prototyping in every case in which it makes *sound business sense*. . . . Our policy is to require competitive prototyping whenever *the risk avoidance to be gained outweighs the costs.*[3] (Italics added.)

The underlying law states that the requirement for competitive prototyping may be waived by the Secretary of Defense based on cost considerations.[4] Though the regulation applies to only one form of prototyping (competitive), the criteria is necessarily general enough to

[2]See DoDI 5000.2, February 1991, p. 5-D-2 and Title 10, United States Code, Section 2365, paragraph (a).

[3]*Inside the Pentagon*, June 13, 1991, p. 12.

[4]Title 10, United States Code, Section 2365, paragraph (c).

apply to other forms of prototyping activities as well. From the perspective of this research, the expressed policy of DoD is consistent with the conceptual framework developed both in this section and in Section 2.

The basic implication, then, is that acquisition policy should reflect only broad guidelines on prototyping, rather than specifying detailed strategies or criteria. This statement is not based on empirical evidence, since we could not effectively relate prototyping to program outcomes. Rather, it follows from the nature and purpose of prototyping—which is highly variable—that there would be no blanket policy that could cover all applications of prototyping. *There is no single approach to prototyping; effective practice involves considerable flexibility, both in tailoring a particular strategy to the needs of a development effort and in using the resulting information.*

We recommend that prototyping be explicitly considered as part of the strategy for development of a weapon system, but that acquisition policy should reflect only broad guidelines on prototyping, rather than attempting to specify detailed prototyping strategies. In other words, we advocate including the full range of prototyping considerations in a rational decision process along the lines described here and illustrated in Figure 6.1 and Table 6.1. There might be situations in which prototyping is not appropriate. Though such cases may be rare, when they do occur, the decision process we are suggesting will allow explicit rationalization as to why prototyping was deemed inappropriate.

There may be other reasons to prototype as well. For instance, certain forms of prctotyping can create and preserve technological and system options, maintain and enhance both the technology and industrial base important to the quality of defense products, and hedge against greater uncertainty in threats. For instance, the interaction of three recent trends suggests a possible new utility for prototyping: limited and declining budgets, an uncertain and rapidly changing military and political environment, and the need to sustain a viable technology and industrial base. Prototyping is a strategy that can theoretically address these concerns. It is generally less expensive than a full-scale development, it requires a supporting technology and production base, and it provides crucial experience to design engineers and managers in both industry and government. Though important, such factors are broader in scope than the issues discussed above, which focus on the application of prototyping to specific weapon system developments. Nevertheless, future research should consider these issues in more detail.

Additionally, both the DoD and Congress should encourage a proper environment for prototyping. If prototyping is to be a useful strategy, the information generated must be incorporated into decisions. This implies the need for a great deal of flexibility by program managers in both government and industry, and a willingness to use the results of prototyping activities to make cost, schedule, and performance trade-offs. Unfortunately, many officials (in the Office of the Secretary of Defense (OSD), the services, and Congress) do not understand that a prototype is successful when it identifies problems. *By its nature, prototyping, properly applied, will produce some "failures."* It needs to be recognized that prototyping is oriented toward identifying problems prior to full commitment to the program.

Appendix A
PROGRAMS INCLUDED IN THE DATABASE

The following list identifies the programs used in this analysis. Aside from the program name, some additional information is provided. The year of first operation identifies the year in which the prototype was (or will be) first operated. Using the narrower definitional criteria discussed in Section 2, an assessment was made as to whether a program meets this prototype definition or not, and whether there was enough information available to make this determination. This addresses the problem of consistent definitions: The use of the term prototype varies considerably in the literature. Lastly, a subjective assessment of the data quality and sources is made with respect to understanding the role and rationale of the prototype in the program.

Table A.1 lists the programs included in the literature database. Programs were identified for potential inclusion if one or more sources indicated that they had, or were planning to have, some type of prototyping activity during the course of development. Most of these programs were included in the database after assessing the reasonableness of the prototyping designation against the definition used in this study. The only other criterion used to determine whether or not to include a program was that the prototype was first operated after 1960. Though the result is not a complete list, it is considered representative of prototyping activities in the post-1960 period.

Table A.2 lists the programs included in the program manager survey. The prototyping designations for these programs are consistent with those of the literature database if the system referenced in the survey is the same as that identified in the literature. Worksheet questionnaires were sent to 85 U.S. government program managers: 43 responses were received.[1] In general, the quality of the data provided by the survey is superior to that of the public literature. While the weapon system classifications that are indicated can be argued (e.g., the V-22 as an aircraft rather than a helicopter), the classifications are those that were indicated by the respondent.

[1]GPS returned three separate worksheets, one each for the space, user equipment, and ground control segments of the program. These are treated separately here as they each had distinct acquisition (and prototyping) strategies.

Table A.1

Programs in the Literature Review Database

Program Name	Year First Operation	Definition[a]	Information
Aircraft:			
X-29A	1984	Yes	Good
X-30 National Aerospace Plane	1993	Yes	Adequate
X-31A	1989	Yes	Adequate
Advanced Fighter Integration Program	1976	Yes	Adequate
Agile Falcon		No	Poor
YF-12/A-11	1964	Yes	Poor
SR-71A/B	1964	?	Poor
YF-7F (A-7 Plus)	1988	Yes	Adequate
A-6F	1987	No	Adequate
F-20	1982	Yes	Good
Skytrader Scout		?	Poor
Hypersonic Glide Vehicle		Yes	Poor
AMX	1984	Yes	Good
Lavi	1986	Yes	Good
Experimental Aircraft Program	1986	Yes	Good
European Fighter Aircraft	1991	Yes	Good
Rafale A	1986	Yes	Good
Rafale D	1990	Yes	Good
Hawk 200	1986	?	Poor
Gripen JAS-39	1987	No	Adequate
AC-130		Yes	Poor
B-70	1964	Yes	Good
C-141A	1963	?	Adequate
C-141B (YC-141B)	1977	Yes	Poor
OV-10A	1965	Yes	Good
Charger	1964	Yes	Good
T-46A	1985	No	Adequate
KC-10A		?	Poor
KC-135R	1982	?	Poor
A-10 (YA-9/10)	1972	Yes	Good
E-3A	1972	Yes	Good
B-1A	1974	Yes	Adequate
B-1B	1984	No	Adequate
E-2C	1971	?	Poor
S-3A	1972	?	Poor
S-3B	1984	?	Poor
E-6A	1987	?	Poor
EF-111	1977	?	Poor
F-14	1970	No	Adequate
F-15	1972	?	Poor
F-15E	1986	Yes	Adequate
F-15 STOL	1988	Yes	Adequate
F-16 (YF-16/17)	1974	Yes	Good
F-16XL (F-16E) SCAMP	1982	Yes	Adequate
F-18L		?	Poor

Table A.1 (continued)

Program Name	Year First Operation	Definition[a]	Information
F/A-18	1978	No	Adequate
T-45TS		?	Poor
Advanced Technology Bomber	1988	?	Poor
F-19		?	Poor
Advanced Tactical Fighter	1990	Yes	Good
Advanced Tactical Aircraft	1990	?	Poor
C-17	1988	No	Poor
Advanced Technology Tactical Transport	1988	Yes	Good
Bromon BR-2000	1988	Yes	Good
AMST (YC-14/15)		Yes	Poor
P-3C	1969	No	Poor
MB.339A	1976	?	Poor
ATM 42	1984	?	Poor
Nimrod	1967	?	Poor
C.101	1977	?	Poor
C-212	1971	Yes	Adequate
C-235	1983	Yes	Adequate
ATL.2	1961	?	Poor
Mirage 2000	1978	?	Poor
Mirage 4000	1979	?	Poor
Super Etendard	1974	?	Poor
EMB-312	1980	?	Poor
FMA IA 58 Pucara	1969	?	Poor
FMA IA 63 Pampa	1984	?	Poor
Arhens		?	Poor
HAL Light Combat Aircraft		?	Poor
Seastar	1984	?	Poor
A-4S-1		?	Poor
A-4K	1987	?	Poor
F1300 Jet Squalus		?	Poor
V-22	1988	?	Adequate
XV-15		Yes	Adequate
V/STOL		?	Poor
XC-142	1963	Yes	Adequate
X-100	1960	Yes	Adequate
X-19	1964	Yes	Adequate
X-22A	1966	Yes	Adequate
CL-84	1965	Yes	Adequate
CL-84-1	1970	Yes	Adequate
SC.1	1960	Yes	Adequate
DO.31E	1967	Yes	Adequate
XV-4B	1968	Yes	Adequate
VAK-191B	1971	Yes	Adequate
XV-5A	1965	Yes	Adequate
XV-4A	1962	Yes	Adequate
XFV-12A	1977	Yes	Adequate
P1127	1961	Yes	Good
XV-6A	1964	Yes	Good

Table A.1 (continued)

Program Name	Year First Operation	Definition[a]	Information
Harrier	1966	?	Poor
AV-8A	1970	Yes	Poor
AV-8B	1978	Yes	Poor
Helicopters:			
CH-53E	1974	Yes	Poor
CH-54 Tarhe	1964	Yes	Adequate
CH-47D	1979	?	Poor
Advanced Scout Helicopter		?	Poor
Advanced Helicopter Improvement Program	1984	?	Adequate
XCH-62		Yes	Adequate
UTTAS (YAH-60/61)	1974	Yes	Good
AH-1 Cobra	1965	Yes	Adequate
AH-56A Cheyenne		?	Poor
AH-64 Apache (YAH-63/64)	1975	Yes	Good
OH-6 Light Observation Helicopter	1963	Yes	Adequate
OH-58A Kiowa	1966	Yes	Adequate
SH-60B LAMPS	1979	?	Poor
VH-60		?	Poor
Light Helicopter Experimental		Yes	Adequate
NOTAR (No Tail Rotor) Helicopter		Yes	Adequate
X-wing		Yes	Adequate
PAH-2		?	Poor
Model 360	1987	Yes	Adequate
H-76	1985	?	Adequate
AH-64B Advanced Apache	1989	?	Poor
A129 Mongoose	1984	?	Poor
SA 365M Panther	1984	?	Poor
EH-101	1987	No	Poor
SA.341 Gazelle	1967	?	Poor
AS.332	1978	?	Poor
NH-90		?	Poor
XH-59A/B Advancing Blade Concept	1975	Yes	Adequate
C-122s	1986	?	Poor
Fuelless RPV	1987	Yes	Adequate
Brave 3000	1983	?	Poor
Sentinel 5000		?	Poor
Missiles:			
Setter	1984	Yes	Good
Avenger		Yes	Adequate
ADATS	1983	Yes	Good
Liberty		Yes	Adequate
Paladin		Yes	Adequate
Tracked Rapier		Yes	Adequate
Tacit Rainbow		?	Adequate
Flexible Lightweight Agile Guided Experiment	1986	Yes	Adequate
Titan III-C		?	Poor

Table A.1 (continued)

Program Name	Year First Operation	Definition[a]	Information
Agenda-D	1962	Yes	Adequate
Laser-Guided Bomb	1966	Yes	Good
Mk-48		?	Poor
Mk-50		?	Poor
Harpoon	1972	?	Poor
Stinger	1976	?	Poor
Dragon	1965	?	Poor
Trident II D-5	1987	?	Poor
GLCM		?	Poor
ALCM		?	Poor
Tomahawk		?	Poor
Sidewinder AIM-9L	1972	?	Adequate
Sidewinder AIM-9M	1978	?	Poor
Hellfire	1978	?	Adequate
Peacekeeper	1983	No	Poor
HARM		?	Poor
AMRAAM	1980	Yes	Good
AAAM		Yes	Adequate
Sea Lance		?	Poor
TOW	1968	?	Poor
Hypervelocity Missile	1987	?	Adequate
ASAT Space Defense		?	Poor
Advanced Anti-Tank Weapon System—Medium		Yes	Adequate
Advanced Strategic Missile System		?	Poor
Earth-Penetrating Warheads		?	Poor
Ballistic Missile Defense System Technology	1979	?	Poor
FOG-M		?	Poor
Long-Range Aircraft Intercept Experiment	1984	?	Adequate
Rolling Airframe Missile	1979	No	Poor
Copperhead		Yes	Adequate
Pershing I		?	Poor
Titan I	1960	?	Adequate
HOT	1971	?	Poor
Short-Range Anti-Tank Weapon		?	Poor
Condor	1971	?	Poor
MLRS Multiple Launch Rocket System	1979	Yes	Good
Land Vehicles:			
M44 Howitzer		?	Poor
LAV Air Defense		?	Poor
M109	1987	Yes	Good
FGH-155		?	Poor
Autonomous Land Vehicle	1987	Yes	Good
Advanced Ground Vehicle Technology		Yes	Good
Integrated Smart Artillery	1986	Yes	Good
Human Factor Howitzer Test Bed	1986	Yes	Good
HMMWV M998	1982	Yes	Good

Table A.1 (continued)

Program Name	Year First Operation	Definition[a]	Information
Dagger		?	Poor
XM800 ARSV		?	Poor
IFV M2/M3 Bradley	1974	Yes	Poor
MBT-70	1967	Yes	Poor
M-1	1976	Yes	Good
M60A4		?	Poor
DIVAD	1980	Yes	Good
Leopard I	1961	?	Poor
NFV-1 IFV		?	Poor
SP122	1984	?	Poor
Heavy Assault Bridge	1984	?	Poor
Counter-Obstacle Vehicle		?	Poor
Improved Vulcan		?	Poor
Teleoperated Mobile Anti-Armor Platform		Yes	Adequate
Voice-Controlled Robotic Vehicle		Yes	Poor
M88 Tank Recovery		?	Poor
Mobile Electronic Warfare System		?	Poor
Stingray Light Tank	1984	Yes	Adequate
VCC-80	1987	?	Poor
Leclerc	1987	?	Adequate
EE-T4 Ogum	1986	?	Poor
MCV-80	1981	?	Poor
Puma IFV	1986	?	Poor
AMX 40 MBT	1983	Yes	Good
AMX 30 MBT	1960	?	Poor
AMX 32 MBT	1979	Yes	Adequate
EE-T2 MBT	1983	?	Poor
EE-T1 MBT	1984	?	Poor
Arjun MBT	1985	?	Poor
K1 MBT	1984	?	Poor
Chieftan 900 MBT	1982	Yes	Adequate
Tk-X MBT	1985	?	Poor
Mk7 MBT	1985	?	Poor
C-1 MBT	1987	?	Poor
76/62 Anti-Aircraft Gun		?	Poor
Fire Ant	1985	?	Adequate
TH-400 Tank Destroyer	1984	?	Poor
SICBM Launcher		?	Poor
Merkava I	1974	Yes	Good
HET-70	1987	?	Poor
M-47		?	Poor
6638 AVH	1985	?	Poor
AS-90 Artillery	1986	?	Poor
Combat Vehicle Reconnaissance (Tracked)	1969	?	Adequate
Subsystems and Other:			
Navstar Global Positioning System	1974	Yes	Good
LANTIRN	1983	No	Good

Table A.1 (continued)

Program Name	Year First Operation	Definition[a]	Information
Airborne Self-Protecting Jammer	1983	?	Good
Joint Tactical Information Distribution System	1977	?	Good
T800 Engine		Yes	Good
Joint-Technology Demonstrator Engine	1989	?	Poor
F404-F2J3		?	Poor
ATF Engine (YF-119/120)	1988	Yes	Good
EJ200 Engine			Poor
XG-40 Engine	1986	?	Poor
XG-15 Engine		?	Poor
GT601 Engine		?	Poor
Advanced-Technology Demonstrator Engine		?	Poor
Modern-Technology Demonstrator Engine		?	Poor
Integrated High-Performance Engine Technologies Initiative		Yes	Adequate
UDF Engine	1988	Yes	Poor
Infrared Search and Track		?	Poor
Common Integrated Processing	1988	?	Adequate
Submarine		Yes	Poor
MIMIC		?	Poor
Superconductors	1987	?	Poor
Thunderbolt	1987	Yes	Adequate
Caseless Ammunition Rifle	1984	Yes	Adequate
Close Assault Weapon		?	Adequate
SHORAD C2		?	Poor
TADS/PNVS	1979	Yes	Adequate
SINCGARS		?	Poor
TACTAS			Poor
BQQ-5 Sonar		?	Poor
SQS-26 Sonar		?	Poor
Hardsite Site Defense		?	Poor
Elevated Kinetic Energy Weapon		?	Adequate
Kinetic Energy Projectile		?	Adequate
MF-30 Cannon	1983	Yes	Poor
Infrared Search and Track Designation System		?	Poor
Anti-Aircraft Command and Control		?	Poor
JSTARS		No	Poor
Combat Identification System		?	Poor
Close-In Weapon System (Phalanx)		?	Poor
105 LGI		?	Poor
RDY Radar	1987	?	Poor
PS-05/A Radar	1986	?	Poor
Tactical Radar Jamming System		?	Poor
Geometric Arithmetic Parallel Processor 1987		?	Poor
Airborne Target Handover System		?	Poor
R21G Radar	1985	?	Poor
AN/APG-67 Radar	1982	?	Poor

Table A.1 (continued)

Program Name	Year First Operation	Definition[a]	Information
GM-15 Countermine		?	Poor
DSP		?	Poor
110X/110E		?	Poor
Rewson		?	Poor
SECS Shipboard Embedded Computer System		?	Poor
CELV		No	Poor
ASPS		?	Poor
SUBACS		?	Poor
Surface Electronic Warfare System		?	Poor
FATDS		?	Poor
LCAC		?	Poor
Patrol Hydrofoil Missile Ship		?	Poor
Aegis Weapon System		?	Poor
SSN-688 Weapon System		?	Poor

[a]A question mark indicates there was insufficient information to make a yes or no designation.

Table A.2

Programs in the Program Manager Survey Database

Program Name	Year First Operation	Definition	Information
Aircraft:			
Advanced Tactical Fighter (ATF)	1990	Yes	Good
AV-8B	1978	Yes	Good
C-17A		No	Poor
F-14		No	Good
F-16	1974	Yes	Good
OV-10D	1987	Yes	Good
T-45TS	1989	No	Good
Helicopter:			
Army Helicopter Improvement Program (OH-58D)	1983	Yes	Good
CH-47D	1978	Yes	Good
Light Helicopter Experiment (LHX)	1993	Yes	Good
V-22		Yes	Good
Missile:			
Advanced Medium Range Air-to-Air Missile (AMRAAM)	1981	Yes	Good
FAAD Line of Sight-Forward-Heavy	1987	Yes	Good

Table A.2 (continued)

Program Name	Year First Operation	Definition	Information
FAAD Non-Line of Sight	1988	Yes	Good
High-Speed Anti-Radiation Missile (HARM)	1987	Yes	Good
Hellfire		Yes	Good
IR Maverick		?	Poor
Mk 50 Tordepo		?	Poor
Pershing II	1982	Yes	Good
Sea Lance	1984	Yes	Good
Short-Range Attack Missile II (SRAM II)	1985	Yes	Good
TOW 2B	1988	Yes	Good
Trident II missile		No	Good
Electronic:			
Advanced Attack Helicopter, Aircraft Survivability Equipment (AAH ASE)	1991	Yes	Good
FAAD C2I		No	Good
GPS-User Equipment	1987	Yes	Good
GPS-Ground Control Segment	1982	Yes	Good
Integrated Defense Avionics Program	1988	Yes	Good
Joint Surveillance and Target Attack System (JSTARS)		No	Poor
Light Airborne Multipurpose System (LAMPS Mk III)		?	Poor
Mk XV IFF	1987	Yes	Good
Mobile Subscriber Equipment (MSE)		Yes	Good
SINCGARS	1989	Yes	Good
Submarine Advanced Combat System (SUBACS)		?	Poor
Tactical Towed Array Sonar (TACTAS)	1988	Yes	Good
Tomahawk	1984	Yes	Good
Vehicle:			
High Mobility Multipurpose Wheeled Vehicle (HMMWV)	1982	Yes	Good
M1 Block II		Yes	Good
Other:			
9mm Pistol	1985	Yes	Good
Advanced Attack Helicopter, Automated Test Equipment (AAH ATE)		No	Good
Copperhead		Yes	Good
Defense Support Program (DSP)		No	Poor
GPS-Space (satellite)	1985	Yes	Good

Appendix B
ADDITIONAL DETAILED DATA TABLES

This appendix contains tables and graphs that provide additional analysis results for both the literature data and the program manager survey. While this information supports and informs the analysis presented in Sections 4 and 5, it was not included directly in the main text for reasons of clarity and presentation. Variables used in these tables and graphs were defined and discussed in Section 3 of the main text.

This appendix has two sections. This first presents supplementary data on prototyping strategies, paralleling the discussion in Section 4. Many of these tables were footnoted in the main text. The second section presents several graphs that describe cost and schedule data for both the literature and survey data.

SUPPLEMENTAL DATA ON PROTOTYPING STRATEGIES

Table B.1 shows the distribution of five levels of specific objectives based on the program manager survey. Given that ranking by importance is implicit here, we again observe that objectives relating directly to technological risk tend to be more frequent at higher-order levels than objectives relating to operational considerations.

Table B.2 illustrates the strong relationships between main purposes and specific objectives, based on the literature data. As expected, technically oriented specific objectives are more often associated with technology-oriented purposes. As the technology used in the weapon system becomes relatively more mature, operational considerations begin to play a larger role. Table B.3 shows similar results for the program manager survey, but the relationship here is less strong.

Table B.1

Distribution of Specific Objectives (Survey Results)

	Obj. 1		Obj. 2		Obj. 3		Obj. 4		Obj. 5	
Category	No.	%	No.	%	No.	%	No.	%	No.	%
Experimental	1	3.2					1	5.6		
Exploratory	1	3.2	1	3.2					1	8.3
Feasibility	7	22.6	5	16.1	3	11.5			1	8.3
Competitive	1	3.2	3	9.7	3	11.5				
Developmental	12	38.7	3	9.7	7	26.9			2	16.7
Political					2	7.7	2	11.1	2	16.7
Integration	1	3.2	11	35.5	3	11.5	6	33.3	1	8.3
Preproduction	6	19.4	3	9.7	3	11.5	1	5.6	1	8.3
Missionized					2	7.7	1	5.6	1	8.3
Operational			4	12.9	2	7.7	4	22.2	2	16.7
Upgrade	2	6.4			1	3.9	1	5.6	1	8.3
Other			1	3.2			2	11.1		
Total	31	100	31	100	26	100	18	100	12	100

Table B.2

General Strategies in Prototyping (Literature Data)

	Main Purpose											
	Technology Viability			Technology Demonstration			System Design			Marketing		
Objectives	I	II	III	I	II	III	I	II	III	I	II	III
Experimental	20	0	0	4	0	0	0	0	0	0	0	0
Exploratory	4	17	0	17	3	0	0	0	0	0	0	0
Feasibility	1	4	3	23	18	1	9	4	0	0	0	0
Competitive	0	0	1	12	2	3	13	0	0	2	0	0
Developmental	0	3	4	1	18	6	5	4	0	4	1	0
Integration	0	0	0	0	4	2	1	5	1	0	0	0
Political	0	0	0	0	0	2	0	1	0	0	1	3
Preproduction	0	0	0	1	1	2	9	2	3	4	4	0
Missionized	0	0	0	0	0	7	0	9	7	0	3	0
Operational	0	0	0	1	1	0	0	1	2	0	1	5
Upgrade	0	0	1	0	0	1	14	0	2	2	1	0
Total	25	24	9	59	47	24	51	26	15	12	11	8

Table B.3

General Strategies in Prototyping (Survey Results)

Specific Objectives	Technology Viability					Technology Demo					System Design					Other	
	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II
Experimental						1			1								
Exploratory	1	1													1		
Feasibility	2	1				4	2	1			1	2	2		1		
Competitive		1					2				1		3				
Developmental		1	2			2	1	3		1	10	1	2		1		
Integration			1	1			2		3		1	8	2	2	1		1
Political								2						2	2		
Preproduction	1							1		1	4	3	2	1		1	
Missionized													2	1			
Operational					1					1		4	2	4	1		
Upgrade											2		1	1			
Other									2			1			1		

NOTES:

(1) There were no programs that had "marketing" as the main purpose, though four had it as secondary purpose.

(2) The number of responses varies across each cross-tab with main purpose:

	No.
Spec. Obj. 1	31
Spec. Obj. 2	31
Spec. Obj. 3	26
Spec. Obj. 4	18
Spec. Obj. 5	12

(3) The program whose main purpose was "other" had only two levels of specific objectives.

Tables B.4 through B.6 demonstrate relationships between the three basic elements of a prototyping strategy: goals, timing, and level of system integration. Tables B.4 and B.5 illustrate that the phase in which prototyping occurs is associated with the level of system integration. Prototypes that occur later in a program tend to be more production representative. Table B.6 shows the relationship between the three elements of prototyping strategy for the program manager survey. The high frequency of prototyping activities with system design purposes that occur during the FSD phase at the full system integration level is notable.

Table B.4

Level of Integration and Program Phase (Literature Data)

	Level of Integration			
Phase Occurring	Full System	Partial System	Subsystem	Total
Concept exploration	0	20	2	22
Demonstration/validation	5	13	1	19
Full-scale development	15	13	8	36
Other (nonprogram)	8	8	4	20
Total	28	54	15	97

Table B.5

Level of Integration and Program Phase (Survey Results)

	Level of Integration			
Phase Occurring	Full System	Partial System	Subsystem	Other
Concept exploration		1	1	
Demonstration/validation	3	2	6	
Full-scale development	8	2	4	
Production	1			
Other	1		1	1

Table B.6

Elements of a Prototyping Strategy (Survey Results)

	Main Purpose			
	Technology Viability	Technology Demo	System Design	Other
Phase occurring				
Concept exploration			2	
Demonstration/validation	3	5	3	
Full-scale development	1	1	12	
Production				1
Other		1	2	
Level of integration				
Full system	1	1	10	1
Partial system		2	3	
Subsystem	3	3	6	
Other		1		

Tables B.7 and B.8 demonstrate the wide variation in prototyping strategies across weapon system types and management agencies for the program manager survey, indicating that at least at an aggregate level, most strategies are generally applicable across systems and management styles.

The program manager survey collected information on contracting strategy. Table B.9 shows the relationship in contract types between phases. While prototyping contracting strategy seems unrelated to production contracting, the relationship to FSD contracting is fairly strong: Similar contracts appear to be used in both phases.

Requirements specification is another aspect of contracting strategy. Table 4.5 in the main text showed this relationship for the prototype phase; Table B.10 shows similar data for FSD and production phases. Some relationship between the form of requirements specification and contract type can be seen. During production, firm fixed-price contracts contain detailed specifications in the contract, as expected. The FSD phase seems more varied.

Table B.11 indicates that requirements were modified as a result of prototyping testing in about half the cases, even if they were specified in detail in the contract. This result is not as counterintuitive as it first seems: Requirements that are specified more loosely do not need to be formally modified as a result of lessons learned through prototyping.

Table B.7

Prototyping Strategies by Weapon Type (Survey Results)

	Weapon Type						
	Aircraft	Helicopter	Missile	Electronic	Vehicle	Other	Total
Main purpose							
Technology viability			1	2		1	4
Technology demonstration	2	1	4				7
System design	2	3	4	6	2	2	19
Marketing							
Other				1			1
Total	4	4	9	9	2	3	31
Prototyping phase							
Concept exploration			2				2
Demonstration/validation	3		4	4			11
Full-scale development	1	3	2	4	2	2	14
Production				1			1
Other		1	1			1	3
Total	4	4	9	9	2	3	31
Level of integration							
Full system	2	3	2	3	1	2	13
Partial system	1		3	1			5
Subsystem	1		4	5	1	1	12
Other		1					1
Total	4	4	9	9	2	3	31

Table B.8

Prototyping Strategies by Agency (Survey Results)

	Management Agency				
	Air Force	Army	Navy	Joint	Total
Main purpose					
Technology viability	1		2	1	4
Technology demonstration	2	2	2	1	7
System design		11	4	4	19
Marketing					
Other		1			1
Total	3	14	8	6	31
Prototyping phase					
Concept exploration		1	1		2
Demonstration/validation	3	1	5	2	11
Full-scale development		10	1	3	14
Production		1			1
Other		1	1	1	3
Total	3	14	8	6	31
Level of integration					
Full system		8	3	2	13
Partial system	1	1	1	2	5
Subsystem	2	5	3	2	12
Other			1		1
Total	3	14	8	6	31

Table B.9

Contract-Type Relationships by Program Phase (Survey Results)

	FSD Contract					
Prototyping Contract	FFP	CPI	CPIw/c	CPFF	Other	Total
FFP	4	0	0	0	4	8
CPI	0	6	0	0	0	6
CPIw/c	0	0	1	0	1	2
CPFF	0	0	0	1	1	2
Other	0	0	0	0	3	3
Total	4	6	1	1	9	21

	Production Contract					
Prototyping Contract	FFP	CPI	CPIw/c	CPFF	Other	Total
FFP	7	0	0	0	1	8
CPI	6	0	0	0	0	6
CPIw/c	2	0	0	0	0	2
CPFF	1	0	0	1	0	2
Other	3	0	0	0	0	3
Total	19	0	0	1	1	21

	Production Contract					
FSD Contract	FFP	CPI	CPIw/c	CPFF	Other	Total
FFP	4	0	0	0	0	4
CPI	7	0	0	0	0	7
CPIw/c	1	0	0	0	0	1
CPFF	0	0	0	1	0	1
Other	10	0	0	0	1	11
Total	22	0	0	1	1	24

NOTES: FFP = firm fixed price; CPI = cost plus incentive; CPIw/c = cost plus incentive w/ceiling; CPFF = cost plus fixed fee.

Table B.10

Contract Type and Requirements Specification (Survey Results)

Form of Requirement	Type of Contract					
	FFP	CPI	CPIw/c	CPFF	Other	Total
Full-Scale Development Phase						
Contract specific	2	5	1		6	14
Performance goal		2		1	2	5
Performance range					1	1
Best effort					1	1
Other	2				1	3
Total	4	7	1	1	11	24
Production Phase						
Contract specific	15					15
Performance goal	5			1		6
Performance range	1				1	2
Best effort	1					1
Other	2					2
Total	24			1	1	26

NOTES: FFP = firm fixed price; CPI = cost plus incentive; CPIw/c = cost plus incentive w/ceiling; CPFF = cost plus fixed fee.

Table B.11

Flexibility to Modify Performance Requirements (Survey Results)

Form of Requirement	Requirements Modification		Total
	Yes	No	
Contract specific	11	5	16
Performance goal	2	5	7
Performance range	1	2	3
Best effort	2	0	2
Other	0	3	3
Total	16	15	31

Table B.12 demonstrates high variation in contract types and the three basic elements of prototyping strategy.

Table B.12

Prototype Contracting and Basic Strategy Elements (Survey Results)

	Main Purpose				
Prototyping Contract	Technology Viability	Technology Demo	System Design	Other	Total
FFP	2	4	5	0	11
CPI	0	3	3	0	6
CPI w/c	0	0	3	0	3
CPFF	1	0	2	0	3
Other	1	1	2	0	4

	Phase in Which Prototyping Occurred					
Prototyping Contract	Concept	Dem./Val.	FSD	Prod.	Other	Total
FFP	0	6	3	0	1	10
CPI	0	3	3	0	0	6
CPI w/c	2	0	1	0	0	3
CPFF	0	1	2	0	0	3
Other	0	1	1	0	1	3

	Level of Integration				
Prototyping Contract	Full System	Partial System	Subsystem	Other	Total
FFP	3	3	4	0	10
CPI	3	1	2	0	6
CPI w/c	1	1	1	0	3
CPFF	0	0	3	0	3
Other	2	0	1	0	3

Tables B.13 and B.14 show some interesting aspects of prototyping strategies. For instance, one possible effect of prototyping is that it may substitute for all or some portion of another program phase. Table B.13 suggests that rather than substituting for another acquisition phase, prototyping tends to complement the traditional phases. This includes verifying and validating other analyses or reducing the overall amount of paper analysis. However, when prototyping is intended to substitute for a conventional development phase, it most likely is intended as a streamlining alternative. The Army's successful Multiple Launch Rocket System (MLRS) program is an example of this type of prototyping.

Table B.13

Prototype Substitution for Other Phases

Relationship of Prototype Phase to Other Phases	Substitute? No	Substitute? Yes	Total
Streamlined alternative	0	1	1
Replaced other phases	0	3	3
Complementary	7	0	7
Verified analysis	3	0	3
Concept/design choice	1	1	2
Reduced amount of analysis	0	2	2
Other	2	0	2
Total	13	7	20

Table B.14

Substitution Effect and Main Purpose

Relationship of Prototype Phase to Other Phases	Main Purpose: Technology Viability	Main Purpose: Technology Demo	Main Purpose: System Design	Total
Streamlined alternative			1	1
Replaced other phases			3	3
Complementary	1	3	3	7
Verified analysis		2	1	3
Concept/design choice		1	1	2
Reduced amount of analysis	1		1	2
Other	1	1		2
Total	3	7	10	20

Whether prototyping was a substitute for another acquisition phase or was complementary in one form or another, there does not appear to be any relationship with the main purpose of the prototyping effort. Table B.14 shows a high variability between the substitution effect and purpose. It is interesting that system design prototypes, which are more often fully integrated systems built during FSD, are the only kind of prototype associated with an actual substitution effect.

Time trends in the elements of prototyping strategy based on the program manager survey (paralleling Tables 4.7–4.9 in the text) are shown in Tables B.15 through B.17. Interestingly, subsystem prototyping does appear to be more common in more recent years, while there do not seem to be strong patterns in main purposes or prototyping phase.

Table B.15

Main Purposes over Time (Survey Results)

Program Initiation	Main Purpose: Technology Viability	Technology Demo	System Design	Other	Total
1970–1974	1	1	7	0	9
1975–1979	0	2	2	1	5
1980–1984	2	3	7	0	12
1985–1989	1	1	2	0	4
Total	4	7	18	1	30

NOTE: Includes only programs meeting strict definition; there were no "marketing" responses.

Table B.16

Prototyping Phase over Time (Survey Results)

Program Initiation	Phase in Which Prototyping Occurred: Concept	Dem./Val.	FSD	Prod.	Other	Total
1970 – 1974	1	2	6	0	0	9
1975 – 1979	0	2	1	1	1	5
1980 – 1984	1	5	4	0	2	12
1985 – 1989	0	2	2	0	0	4
Total	2	11	13	1	3	30

NOTE: Includes only programs meeting strict definition.

Table B.17

Level of Integration over Time (Survey Results)

Program Initiation	Level of Integration: Full System	Partial System	Subsystem	Other	Total
1970 – 1974	5	3	1	0	9
1975 – 1979	4	1	0	0	5
1980 – 1984	3	1	7	1	12
1985 – 1989	1	0	3	0	4
Total	13	5	11	1	30

NOTE: Includes only programs meeting strict definition.

COST AND SCHEDULE DATA

This section presents some of the cost and schedule data collected from both the literature and the program manager survey. This information is presented here rather than in the main text, as it is not directly relevant to the main arguments of this research. In general, relationships between cost, schedule, and prototyping are fairly weak and are in the directions we might expect based on other research. No strong implications for prototyping strategies can be drawn. However, cost and schedule estimates are important parts of any prototyping strategy, and cost and schedule outcomes are one (indirect) way of measuring the relative success or failure of that strategy.

Figure B.1 shows the costs of prototyping and total development (in constant FY82 dollars) for the literature data as a function of the year of program initiation, measured as the Milestone I (or equivalent) date. No strong pattern emerges. Consistent with prior research, prototyping appears to remain a relatively small part of development costs. Figure B.2 shows just the prototype costs: with a few exceptions, most prototypes in this data set cost under $400 million (FY82$).

Figure B.3 shows similar data for the programs in the program manager survey (in constant FY89 dollars). The same basic distribution is apparent. Figures B.4 and B.5 show the cost of the prototype as a percent of development costs and total program costs respectively. While the cost of prototyping can be a large part of development cost, it is generally a fairly small portion of total program costs.

Schedule data are shown in Figure B.6 for the literature database. Design time is measured as the months between program start and first prototype operation. The length of the prototyping phase includes design time, but extends to the end of the prototyping test phase when (hopefully) the objectives have been achieved. Total program duration is measured as the time between program start (Milestone I or equivalent) and first operational delivery. Figure B.7 shows that the length of the prototyping phase as a percent of total program duration has been decreasing.

Figures B.8 through B.11 provide some detail on prototype-related schedule trends using the program manager survey. The length of the prototyping phase (Figure B.8, measured as above) and the prototype design time (Figure B.9, measured as above) have varied considerably over time, but no strong pattern emerges. On the other hand, both the time from program start to first operation (Figure B.10) and the time to when prototyping objectives have been achieved (Figure

B.11) have decreased. Reasons for that change are not currently known.

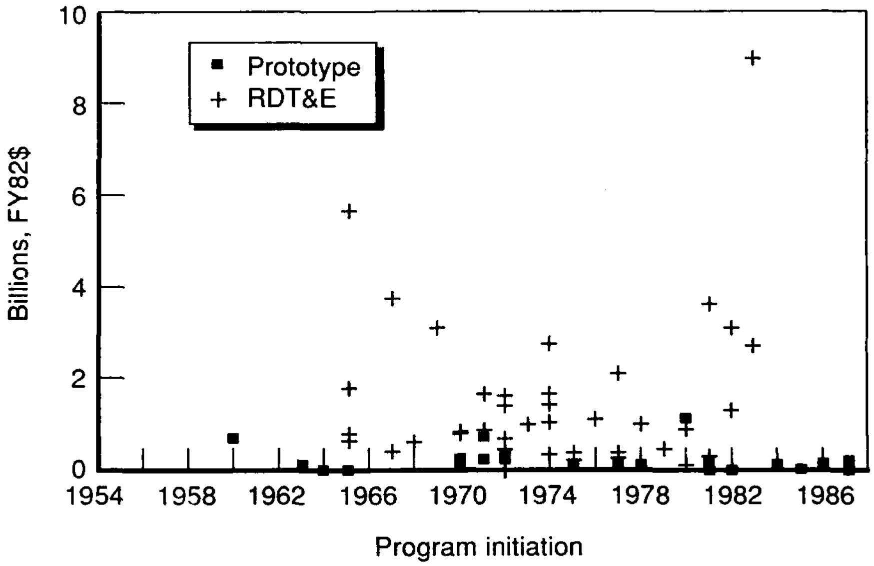


Figure B.1—Cost Trends over Time (Literature Data)

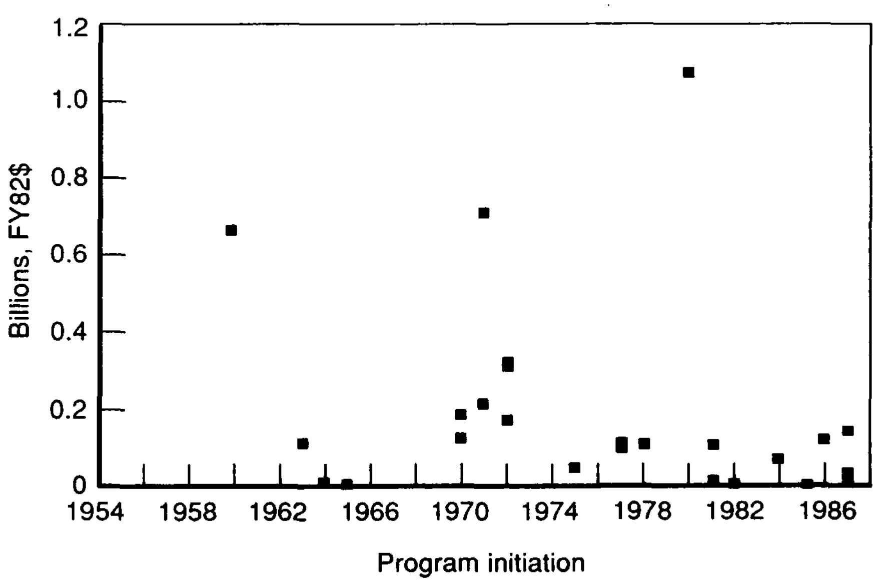


Figure B.2—Prototype Cost Trends (Literature Data)

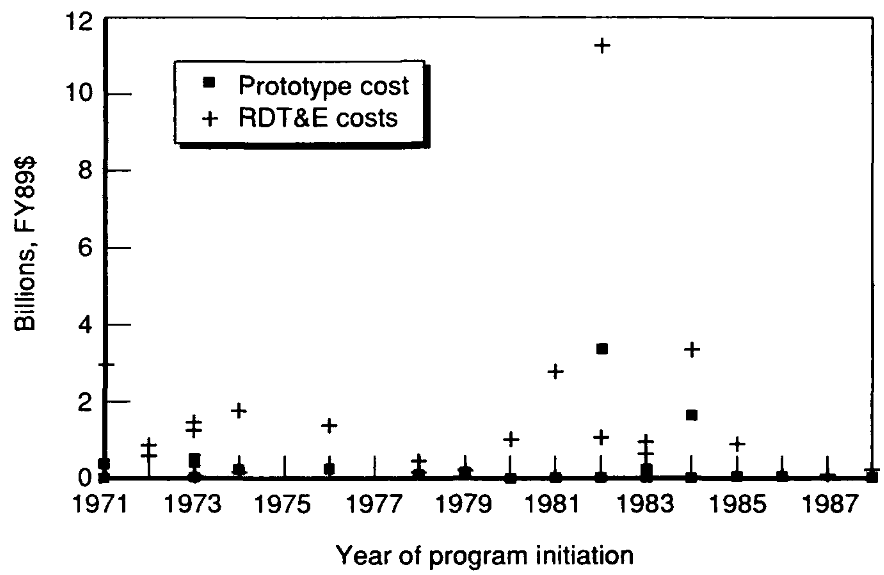


Figure B.3—Costs over Time (Program Manager Survey)

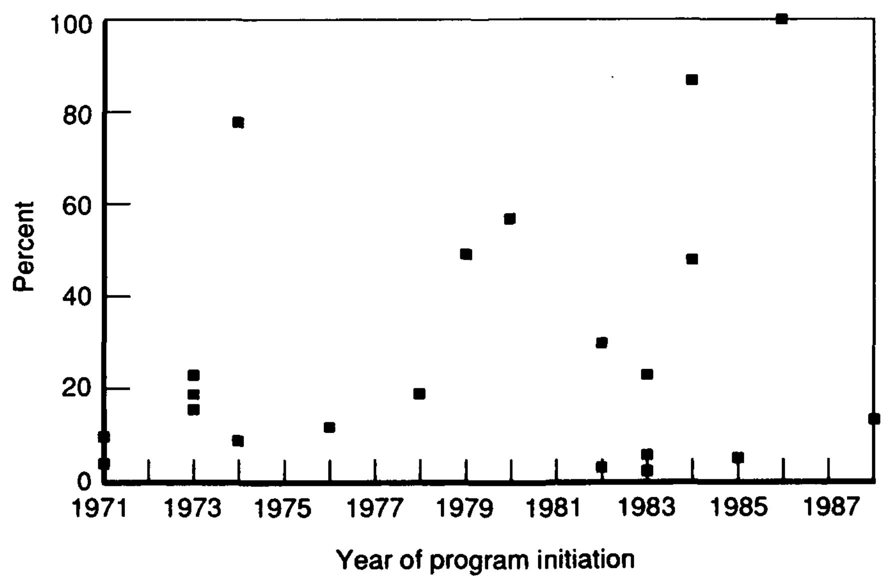


Figure B.4—Prototype Cost as a Percent of RDT&E (Program Manager Survey)

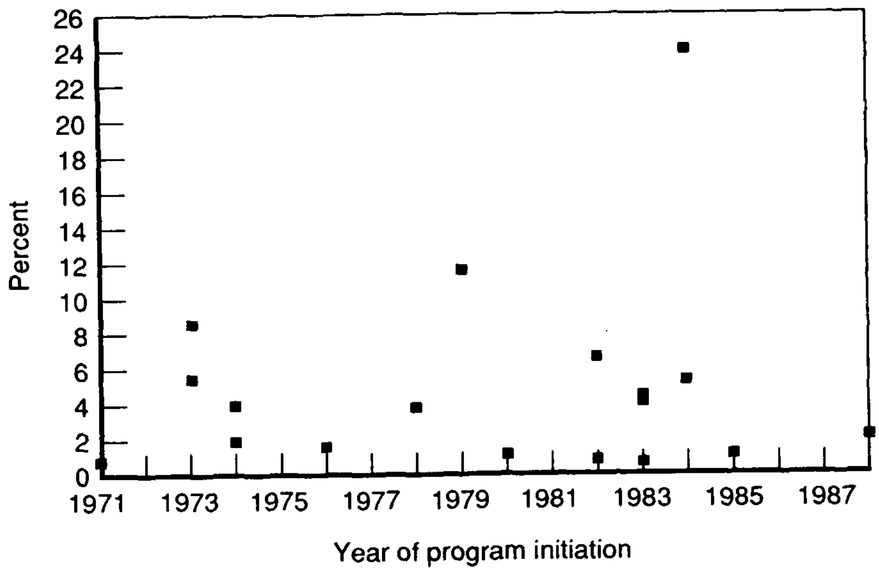


Figure B.5—Prototype Cost as a Percent of Total Cost (Program Manager Survey)

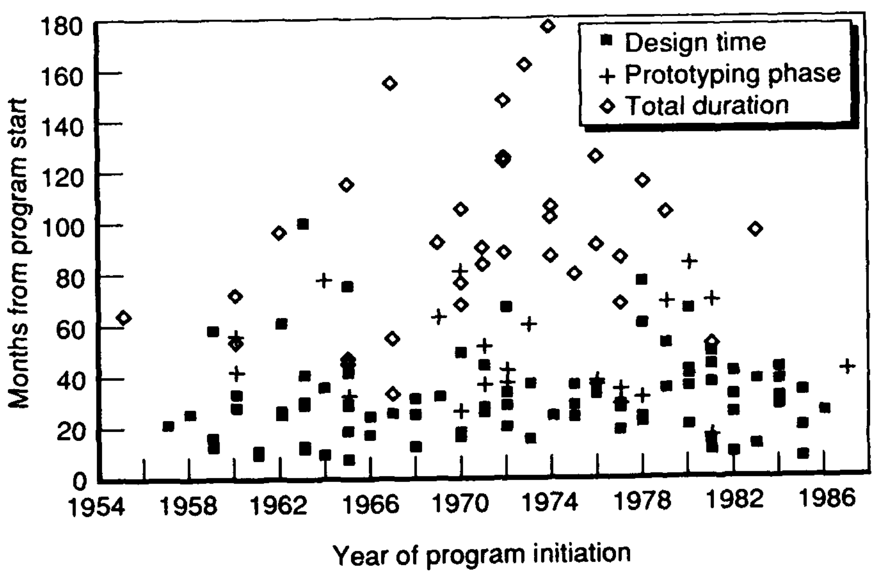


Figure B.6—Schedule Trends (Literature Data)

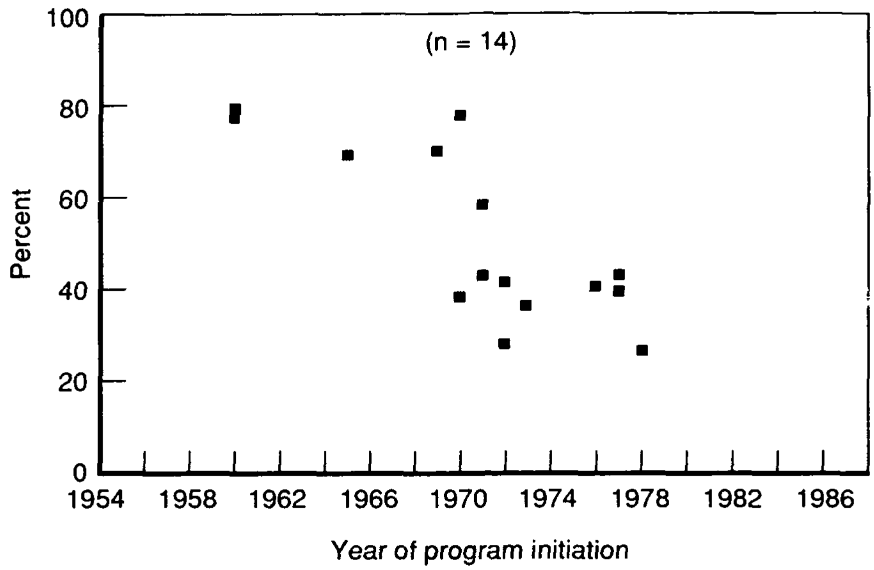


Figure B.7—Prototype Phase as a Percent of Program Length (Literature Data)

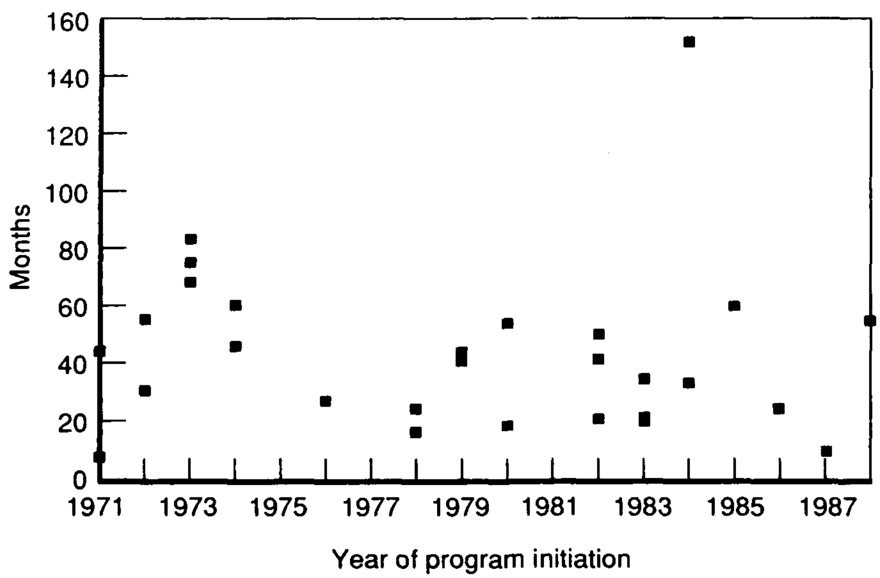


Figure B.8—Length of Prototyping Phase (Program Manager Survey)

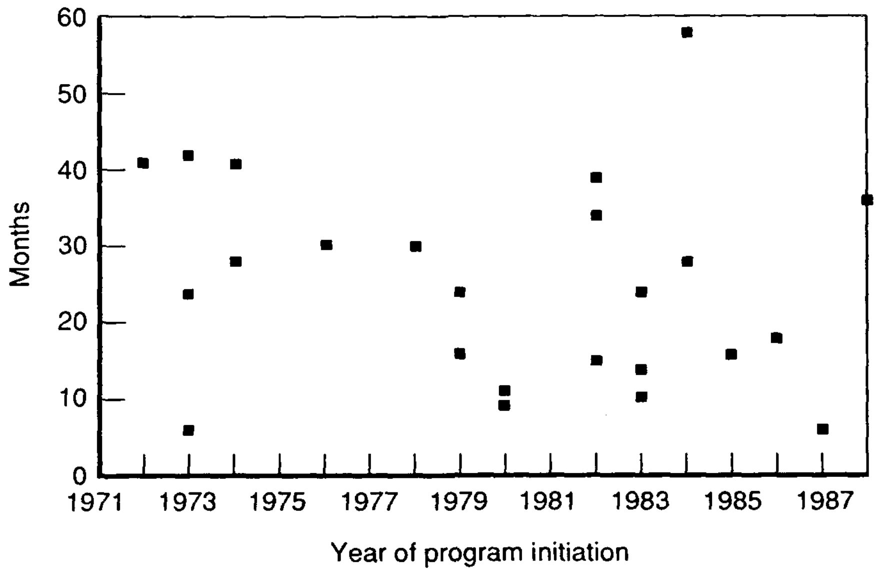


Figure B.9—Prototype Design Time (Program Manager Survey)

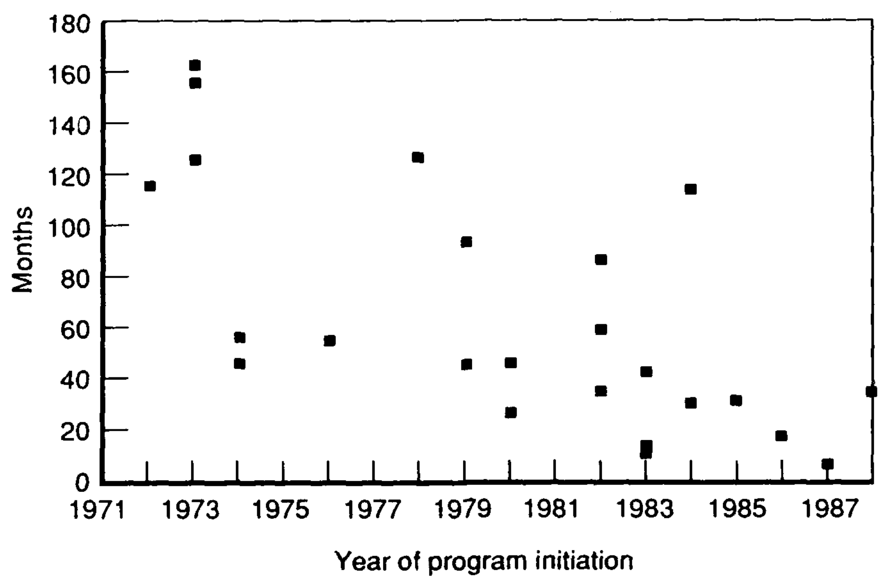


Figure B.10—Time to First Prototype Operation (Program Manager Survey)

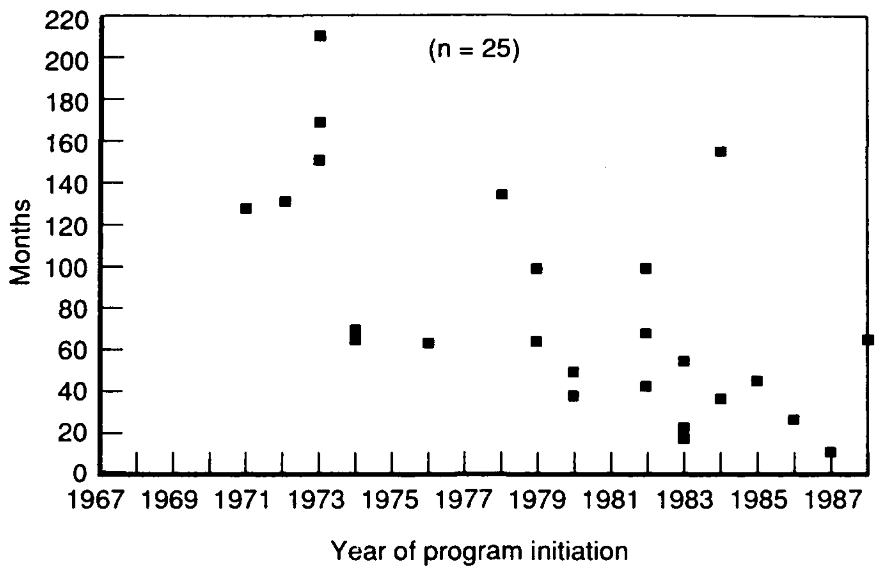


Figure B.11—Time to Achieve Prototyping Objectives (Program Manager Survey)

Appendix C
PROTOTYPING STRATEGY WORKSHEET

A major part of the research design for this analysis was the design of a prototyping strategy worksheet as a mechanism for collecting information on current prototyping activities. The worksheet is presented here. It was sent to the government program managers of 85 current U.S. weapon system programs: 43 responses were received covering 41 programs (listed in Table A.2). In most cases, there was at least one follow-up phone conversation after receipt of the worksheet.

The worksheet consists of four sets of questions: general information, management issues, cost and schedule, and technology and performance. Most of the questions are qualitative in nature and the answers were therefore subjective. The focus of the worksheet is on the role of the prototype or prototyping phase *in the program and the* usefulness of the prototyping activities with respect to achievement of program objectives.

At the time the survey was implemented, data of this sort had never before been collected and analyzed for this many programs.

3/18/88

PROTOTYPING STRATEGY WORKSHEET

PERSON COMPLETING WORKSHEET:

Name: ______________________________

Title: ______________________________

Years at Position: ___________________

Phone Number: ______________________

DATE COMPLETED: ____________________

Recently there has been increased interest in the use of prototyping during weapon system development. Prototyping held a prominent place in the Packard Commission report, Congress is now encouraging the use of prototypes, and prototyping is now formally a part of DoD regulations governing major weapon system development (DoDI 5000.2). However, there remain questions such as what a prototype is, under what conditions it makes sense to prototype and what the benefits of prototyping might be. The Office of the Undersecretary of Defense (Acquisition) is sponsoring a RAND Corporation study of prototyping activities which begins to address these questions.

The purpose of this worksheet is to collect previously unavailable information from various weapon system development programs. These data will be aggregated to test hypotheses regarding the uses of prototypes and the relationship between prototyping activities and the acquisition environment.

Though a considerable effort has been made to limit the amount of information that is needed, we recognize that the requested information is rather extensive. We have, therefore, designed the questions to be mostly subjective in nature. The worksheet should be completed by someone in the Program Office closely connected with the program (e.g., program manager or deputy, or chief engineer). All information that would allow identification of a specific program will be treated as confidential by RAND. Please feel free to call your RAND contact (collect) if you have any questions.

RAND CONTACT: Jeff Drezner

TELEPHONE: (213) 393-0411

GLOSSARY

Prototype: An article fabricated in the expectation of change, often in the demonstration validation phase. Prototypes differ from full-scale development articles in terms of their goals and the subsequent decisions affected. This implies that the results of the prototype phase will be the basis for one or more major decisions, such as cost, schedule, and performance trade-offs, or program termination, prior to commitment to full-scale production. For any given program, there may be one or more of several different kinds of prototypes.

Prototype Phase: Phase of the acquisition process concerned with design, fabrication, and testing of prototypes. May be a portion of the time or the entire time between major decision milestones, or it may cut across decision milestones. This phase often corresponds with the demonstration validation phase.

Other Phases: Phase(s) of the acquisition process not directly concerned with prototyping: may include all or part of concept exploration, demonstration/validation, full-scale development, low-rate initial production, full-scale production.

Program Initiation: Formal point in time at which program was begun. May coincide with Milestone "0" or I, establishment of Program Office, or some other event.

Demonstration/ Validation: Phase I or equivalent.

Full-Scale Development: Phase II or equivalent.

Low-Rate Initial Production: Milestone IIIa or equivalent.

Full Production: Milestone III or IIIb decision.

I. GENERAL INFORMATION

Program Name: ______________________________

1. Weapon/System Type:

   (Check One)

   ☐ Fixed-Wing Aircraft

   ☐ Helicopter

   ☐ Missile, Bomb, Torpedo

   ☐ Communications, Navigation

   ☐ Other - Specify: ______________________________

2. Weapon/System Function or Mission: ______________________________

   ____

3. Management Agency:

   (Check One)

   ☐ Air Force

   ☐ Army

   ☐ Navy/Marine Corps

   ☐ Joint - Specify: ____________________

4. Does the term "prototype" have a specific meaning in the context of your program? Please explain.

   ____

   ____

   ____

   ____

   ____

   ____

5. Do you distinguish between prototypes and other kinds of preproduction articles in your program? Please explain.

____

____

____

6. What was (is) the overall purpose of prototyping in the program: What were (are) *the expected benefits of including a prototype phase?*

____

____

____

____

7. Describe the effect of the prototype phase on the overall program. The interest here is on how the information generated during the prototype phase was (will be) used. For example, were (will) cost and schedule estimates (be) improved or adjusted based on the results of the prototype phase? *Did (will) information from* the prototype cause performance requirements to be adjusted?

____

____

____

____

____

____

8. For each of the following levels, indicate if there was a prototype and if so, the number of prototypes built. For example, an engine/platform combination counts as a partial system prototype, and adding fully integrated electronics to the powered platform produces a full system. The definitions for each level of prototyping are provided below.

Level of Prototyping	No	Yes		Number
Full System....................	☐	☐	---> How many?	_____
Partial System	☐	☐	---> How many?	_____
Subsystem	☐	☐	---> How many?	_____
Component	☐	☐	---> How many?	_____

Other - Explain ____________________________

Definitions

Full System:	Fully integrated unit, with all key subsystems included, in final or close to final configuration.
Partial System:	Less than fully integrated system, with some key subsystems included, not necessarily final form.
Subsystem:	Key parts of weapon system which are "stand alone" (e.g., platform, propulsion, various types of electronics, gun system).
Components:	Building blocks of subsystems (e.g., Very High Speed Integrated Circuits VHSIC).

9. Many of the remaining questions in the worksheet should be answered with a single prototype article in mind. Please indicate which level of prototyping (see Question 8) you chose and within that level which prototype if there is more than one at that level. Briefly explain why you chose that prototype. Our preference is for the one you believe contributes the most to achieving the objectives of the program.

____

____

____

____

____

____

10. *We would like to know the purpose or use of the prototype you have chosen (see* Question 9). Attachment A is a taxonomy we have developed for classifying prototypes. Using this taxonomy, we would like you to classify the prototype. In the boxes below, first indicate which of the general purposes apply, by entering the corresponding letter, and note secondary purposes if any. Next, indicate the specific objectives associated with the prototype by entering the corresponding numbers in decreasing order of importance. If the categories described do not capture the objectives adequately, please use your own term to describe the objective.

<u>Main Purposes</u>

A. Uncertainty Reduction
B. Technology Demonstration
C. System Design/PerformanceValidation
D. Marketing
O. Other - Specify:

____
____

<u>Specific Objectives</u>

1. Experimental
2. Exploratory
3. Feasibility
4. Competitive
5. Developmental
6. Political
7. Integration
8. Preproduction
9. Missionized
10. Operational
11. Upgrade
12. Other
Specify: ____________

____

Main Purpose	Secondary Purpose (If exists)	Specific objectives in decreasing order of importance			

II. MANAGEMENT

Questions 11 through 13 are about the prototype you selected in Question 9.

11. How were (will) the performance requirements (be) specified for the prototype?

(Check One)

- ☐ Specific Contract Requirements
- ☐ Performance Goal
- ☐ Performance Range
- ☐ Best Efforts
- ☐ Other - Specify: ______________________________

12. Were (Will) the performance requirements for the final system (be) modified as a result of prototype testing? This includes reliability and maintainability requirements. Please explain.

____

____

____

____

____

13. Indicate the type of contract used for the prototype phase and then for the full-scale development and procurement phases of the program.

	Prototype	FSD	Procurement
	(Check One In Each Column)		
Firm Fixed Price	☐	☐	☐
Cost + Incentive	☐	☐	☐
Cost + Incentive with ceiling	☐	☐	☐
Cost + Fixed Fee	☐	☐	☐
Other - Specify: ________	☐	☐	☐

____

14. Did (Will) the prototype and associated testing substitute for, or provide an alternative to, other kinds of analysis or development steps? Please explain.

____

____

____

____

____

____

Questions 15–19 refer to the entire program.

15. As compared to a similar *nonprototype development program*, how would you rate the amount of documentation and reporting required in the prototype phase of the program?

(Circle One Number)

1	2	3	4	5
Less		Same		More

16. Beginning with program initiation, for each year of the program, what was the average professional staff size (number of full-time equivalents) in the system program office?

Fiscal Year	#	Fiscal Year	#	Fiscal Year	#
________	____	________	____	________	____
________	____	________	____	________	____
________	____	________	____	________	____

17. Indicate the number of organizational layers between the Project Manager and the person who can authorize major program changes during the prototype phase, full-scale development and during production. A major program change might constitute a reduction or increase in performance, the addition or subtraction of a mission requirement, schedule stretches, or cost increases.

Layers During Prototype Phase ______

Layers During Full-Scale Development ______

Layers During Production Phase ______

18. Indicate who (position, not name) the top decision maker was (will be) for each of the following types of changes.

Cost changes ____________________

Schedule changes ____________________

Performance changes ____________________

19. Was there (Will there be) industry teaming on this project?

(Check One)

☐ Yes

☐ No

III. COST AND SCHEDULE

20. Indicate the cost to the government (actual or most current estimate) in constant dollars for the following. The cost of the prototype phase is a subset of RDT&E expenditures and includes engineering, tooling, hardware and testing costs associated with the prototype. Also, indicate the quantity associated with the cost figure provided. Of interest here is the cost of the prototype phase as a percent of total RDT&E and procurement costs.

	Dollars	Year Dollars In	Quantity
Research, Development, Test & Evaluation	$ _____	19 _____	_____
Prototype (all prototypes)	$ _____	19 _____	_____
System Procurement	$ _____	19 _____	_____

21. Indicate the actual or most current schedule estimates for the following program milestone dates:

Program Initiation	☐☐/☐☐ MO YR	---> Specify Event _____
Demonstration/Validation (Milestone I)	☐☐/☐☐ MO YR	
Full-Scale Development (Milestone II)	☐☐/☐☐ MO YR	
Low-Rate Initial Production (Milestone IIIa)	☐☐/☐☐ MO YR	
Full Production (Milestone IIIb)	☐☐/☐☐ MO YR	

22. For the prototype selected indicate the actual or most current estimate of dates that the following occured or will occur. Objectives achieved refers to the date at which information generated by prototype testing was sufficient to move on to the next phase in the program.

Design Start	Fabrication Start	First Operation	Objectives Achieved
☐☐/☐☐ MO YR	☐☐/☐☐ MO YR	☐☐/☐☐ MO YR	☐☐/☐☐ MO YR

23. Please indicate the start and completion dates for the entire prototype phase.

START ☐☐/☐☐ Month Year COMPLETION ☐☐/☐☐ Month Year

24. When was the decision made to prototype?

ENTER DATE ☐☐/☐☐ Month Year

24a. Who made this decision (position)? ____________

25. Was the prototype phase planned from the outset?

(Check One)

☐ Yes

☐ No

IV. TECHNOLOGY AND PERFORMANCE

26a. Was (Is) the advance sought in the overall program evolutionary (relatively small increase in technological advance building on the existing state of the art as represented by existing systems) or revolutionary (major innovative technological advance over current systems).

(Check One)

☐ Evolutionary

☐ Revolutionary

26b. What system did you use as a basis for deciding whether this program was evolutionary or revolutionary?

____

27. What were (will be) the most difficult technical challenges in the overall program?

____

____

____

____

28. Describe the role of the prototype phase in meeting these challenges.

____

____

____

____

____

29. Describe the fabrication methods used (to be used) to build the prototype selected. Include whether CAD/CAM was (will be) used and how prototype fabrication differs from production fabrication (e.g., same or different plant, tooling, etc.).

____

____

____

____

____

30. How would you rate the skill level of the contractor personnel involved in the prototype phase compared to those used by the contractor in the rest of the program? For example, it is sometimes the case that smaller, more highly skilled design teams are used by the contractor for prototype design, fabrication, and testing.

(Circle One Number)

1	2	3	4	5
Less Skilled		Same		More Skilled

31. What additional information do you feel would be needed to help us fully understand the prototyping activities in your program?

____

____

____

____

____

Attachment A

There are four general purpose categories: uncertainty reduction, technology demonstration, design/performance, and marketing. These categories represent the overall purpose or use of the prototype and are closely related to the expected benefits of the prototype and the decision stage of the program.

1. **Uncertainty Reduction:**

   This purpose is oriented toward generating information to reduce technological risk in a general sense. These are "building block" prototypes, meaning that they add to the general knowledge base. These prototypes generally occur early in a program (before demonstration/validation at Milestone I). No military mission needs to be specified.

2. **Technology Demonstration:**

   This purpose concerns exploring the possible performance envelope of a system. The prototypes in this category are often used for exploring the usefulness of a new design or concept to meet a mission, and demonstrations or a particular application of technology. Prototypes in this category are also used to generate or preserve design and concept options as a hedge against threat uncertainty. Missions or functional requirements are often specified. These prototypes may occur early in the program in concept exploration or validation phases at a time when the design is not frozen. Production is often anticipated.

3. **System Design/Performance Validation:**

   This purpose relates to prototype uses involving design/performance specifications or requirements. Also included here are demonstrations of the ability to meet a specified threat, contract specifications, and producibility concerns. Missions are specified, often in detail, and there is an expectation of production. Operation, support, and logistics are also of concern. This category might also be called "engineering" as these prototypes are often fabricated as part of advanced development or full-scale engineering effort.

4. **Marketing:**

   This category refers to uses having to do directly with selling a product or supporting a proposal. These are often close to production configuration or missionized. Competition is a frequent use here, or some other variation on the theme that "mine is better than yours." These prototypes can be part of any decision phase prior to production, and there is a definite expectation for production. Missions do not need to be specified, though the prototype is always oriented toward a specific functional requirement. These prototypes are sometimes funded by private industry.

Specific objectives are the next level of purpose below the general purpose. This level explicitly recognizes that there are many possible specific uses for prototypes, and that several objectives might be appropriate for one prototype. Specific objectives may also cut across the boundries of the main purpose categories and relate to the specific uses a prototype was built for, and/or to the specific information generated. There are 11 specific objectives listed and defined below:

- Experimental: Demonstrates a new idea, new technology, or existing technology in a new application. Usually occurs very early in the program and may not have a particular mission or expectations of production.

- Exploratory: Evaluates possible performance envelope or tests feasibility of performance requirement. May not have mission specified or expectations of production, but does have explicit performance goals. Usually occurs in concept or validation phase.

- Feasibility: Demonstrates performance objectives in reference to a specific mission. Usually occurs in validation phase, though production may not be expected.

- Competitive: Used to improve source-selection decisions in validation or FSD phases. Production is anticipated.

- Developmental: Determines the tactical or operational suitability for military uses. May occur in concept or validation phases. This is the missionized version of an experimental prototype.

- Political: Achieves some political or corporate strategy objective, or demonstrates attainment of a political objective, or responds to a politically established requirement. Can occur throughout the decision process, though it occurs most often in validation or FSD.

- Integration: Tests subsystem matching and full system operation. May be part of concept, validation, or FSD phases. Specific mission or functional requirement exists.

- Preproduction: Tests production configuration, after design freeze, usually during FSD. Full rate production is expected.

- Missionized: Evaluates performance with respect to specified threat using fully integrated system. May occur in concept, validation, or FSD phases.

- Operational: Tests operational suitability of fully integrated system, including reliability, availability, and maintainability characteristics. Also used for doctrine development and integrated logistics support planning.

- Upgrade: Tests or demonstrates subsystem improvement to existing system in operational use. Occurs during production phase of existing platform, but the upgrade itself may be part of a concept, validation, or FSD phase.

BIBLIOGRAPHY

PROTOTYPING: GENERAL

"Advanced Prototype," Hearing Before the Committee on Armed Services, United States Senate, Government Printing Office, Washington, D.C., September 9, 1971.

Burbey, Gene P., *Development Prototyping/Integrated Logistics Support (Complementary Concepts or a Dichotomy)*, Defense Systems Management School, May 1973.

Conrow, E. H., G. K. Smith, and A. A. Barbour, *The Joint Cruise Missiles Project: An Acquisition History*, RAND, R-3039-JCMPO, August 1982.

"DARPA Prototype Projects May Include BGV, Mini GPS, LIGHTSAT, Armor, Torpedoes," *Inside the Pentagon*, 17 April 1987, Vol. 3, No. 16, pp. 1, 6–7.

DeLeon, Peter, *The Laser Guided Bomb: Case History of a Development*, RAND, R-1312-1-PR, June 1974.

Dews, Edmund, Giles K. Smith, Allen Barbour, Elwyn Harris, and Michael Hesse, *Acquisition Policy Effectiveness: Department of Defense Experience in the 1970s*, RAND, R-2516-DR&E, October 1980.

DoD Instruction 5000.2, "Defense Acquisition Program Procedures," September 14, 1987.

Drezner, Jeffrey A. and Giles K. Smith, *An Analysis of Weapon System Acquisition Schedules*, RAND, R-3937-ACQ, December 1990.

Evans, James A., *Potential Adverse Effects of Competitive Prototype Validation*, Defense Systems Management College, November 1974.

Final Report to the President by the President's Blue Ribbon Commission on Defense Management, *A Quest for Excellence*, June 1986.

Georgallis, P. C., "Terms and Definitions of Prototyping," *Prototyping*, Chapter 3, Ramcor, Inc., Vienna, VA, 29 December 1972.

Glennan, Thomas K., Jr., *Issues in the Choice of Development Policies*, RAND, P-3153, October 1965.

Hackworth, Robie, "Development-Production Versus Milestones and Prototyping in Military Aircraft Acquisition," Thesis, Air War College, April 1972.

Holzer, Robert and George Leopold, "DoD Pushes Prototypes," *Defense News*, June 25, 1990, p. 4.

Klass, Philip J., "DARPA Will Team with Services to Develop Prototype Weapons," *Aviation Week & Space Technology*, 4 May 1987, pp. 97, 100.

Klein, B. H., T. K. Glennan, Jr., and G. H. Shubert, *The Role of Prototypes in Development*, RAND, RM-3476-PR, February 1963.

Leopold, George, "DARPA Prototyping Office Due Funding Infusion," *Defense News*, 22 June 1987, p. 15.

Lyons, Robert P., *The Search for an Advanced Fighter: A History from the XF-108 to the Advanced Tactical Fighter*, Air University, April 1986.

Masiello, Louis D., "Contract Definition Versus the Competitive Prototype Approach: A Comparative Analysis," Thesis, Air University, May 1970.

Nelson, J. R., and J. R. Gebman, with J. L. Birkler, R. W. Hess, P. Konoske-Dey, and W. H. Krase, *Future V/STOL Airplanes: Guidelines and Techniques for Acquisition Program Analysis and Evaluation*, RAND, N-1242-PA&E, October 1979.

Nelson, J. R., P. Konoske-Dey, M. R. Fiorello, J. R. Gebman, G. K. Smith, and A. Sweetland, *A Weapon-System-Life-Cycle Overview: The A-7D Experience*, RAND, R-1452-PR, October 1974.

Packard, David, "Improving R&D Management Through Prototyping," *Defense Management Journal*, July 1972, p. 5.

Perry, Robert, *A Prototype Strategy for Aircraft Development*, RAND, RM-5597-1-PR, July 1972.

Perry, Robert, Giles K. Smith, Alvin J. Harman, and Susan Henrichsen, *System Acquisition Strategies*, RAND, R-733-PR/ARPA, June 1971.

Perry, Robert, *A Dassault Dossier: Aircraft Acquisition in France*, RAND, R-1148-PR, September 1973.

"Prototyping: A Key to Decision Making," *Defense Management Journal*, July 1972.

A Quest for Excellence, Final Report to the President by the President's Blue Ribbon Commission on Defense Management, June 1986.

"Rapid Prototyping: Its Role in the Acquisition Process," *Signal*, Fairfax, VA. September 1987, M, 33, 518.

Report to the Congress by the Comptroller General of the United States, *Evaluation of Two Proposed Methods for Enhancing Competition in Weapons Systems Procurement*, 14 July 1969, B-39995.

Rich, Michael and Edmund Dews, with C. L. Batten, Jr., *Improving the Military Acquisition Process: Lessons from RAND Research*, RAND, R-3373-AF/RC, February 1986.

Richanbach, Paul H., et al., *The Future of Military R&D Towards a Flexible Acquisition Strategy*, Institute of Defense Analysis, July 1990, P-2444.

Rothenberg, Jeff, *Prototyping as Modeling: What Is Being Modeled?* RAND, N-3191-DARPA, July 1990.

Seminar on Prototyping, Presented by the National Security Industrial Association, 22–23 February 1972, St. Louis, Missouri.

Shapiro, Robert J., "A Frightening New Numbers Game," *U.S. News and World Report*, 28 September 1987, pp. 8, 13, 32.

Smith, G. K., A. A. Barbour, T. L. McNaugher, M. D. Rich, and W. L. Stanley, *The Use of Prototypes in Weapon System Development*, RAND, R-2345-AF, March 1981.

Smith G. K. and E. T. Friedmann, *An Analysis of Weapon System Acquisition Intervals, Past and Present*, RAND, R-2605-DR&E/AF, November 1980.

Stanley, William L., Michael D. Miller, *Measuring Technological Change in Jet Fighter Aircraft*, RAND, R-2249-AF, September 1979.

Thompson, William E., III, "Risk Implications for Cost Growth in Weapon System Acquisition," *Concepts—The Journal of Defense System Acquisition Management*, Spring 1982, Vol. 5, No. 2.

Tyson, Karen W., J. Richard Nelson, Neang I. Om, and Paul R. Palmer, *Acquiring Major Systems: Cost and Schedule Trends and*

Acquisition Initiative Effectiveness, Institute for Defense Analyses, March 1989, P-2201.

U.S. Congress, *Restructuring Defense: Transitioning the Defense Industrial Base,* Office of Technology Assessment, July 1991.

AIRCRAFT

"A-6F Will Do the Job Until ATA," *Jane's Defence Weekly*, 15 August 1987, p. 255.

"Advanced Apache Under Consideration," *International Defense Review*, August 1987, p. 1000.

"Agusta A129 Mangusta (Mongoose)," *Air Force Magazine,* October 1986, pp. 100–101.

"AMX Rolled Out," *Aviation Week and Space Technology*, 16 July 1987, p. 25.

"Anti-Tank Helicopters: United States—LHX at the Expense of Apache," *International Defense Review*, May 1987, Vol. 20, pp. 603–614.

"Bell Helicopter Textron and Boeing Vertol Co.'s XV-15 Tilt-Rotor Aircraft," *Defense News*, 3 August 1987, Vol. 2, No. 31, p. 1.

Bernstein, James, "Rockwell's X-31 Has a Foreign Accent," *Long Island Newsday*, 16 September 1987, p. 53.

Beyers, Dan, "Advanced Missiles Prompt U.S. to Probe Better Fighter Aircraft Maneuverability," *Defense News*, 10 August 1987, pp. 1, 24.

Beyers, Dan, "DARPA Retreats from Air Force Plan," *Defense News*, 17 August 1987, p. 4.

Beyers, Dan, "Dassault Test Pilot Touts Rafale's Performance," *Defense News*, 22 June 1987, p. 3.

Beyers, Dan, "Flexible-Winged F-111 Begins New Round of Flight Testing," *Defense News*, 24 August 1987, pp. 21, 32.

Beyers, Dan, "Navy Will Avoid Major Changes to Structure of F/A-18 Hornet," *Defense News*, 24 August 1987, p. 36.

Beyers, Dan, "Pentagon Seeks Ambitious F-16 Upgrade Plan," *Defense News*, 12 October 1987.

Beyers, Dan, "Senate Earmarks $10 Million for Improved A-7 Aircraft," *Defense News*, 28 September 1987, p. 44.

Beyers, Dan, "Technical Glitches Threaten Cost Overrun of $100 Million on X-Wing Development," *Defense News*, 24 August 1987, p. 3.

"Boeing Brave 3000," *Air Force Magazine*, August 1987, pp. 103–104.

"Boeing Vertol Model 360 Helicopter to Undergo Performance, Stability Tests," *Aviation Week and Space Technology*, 13 July 1987, p. 143.

"Boeing Vertol's Model 360 Makes its Maiden Flight," *International Defense Review*.

Brown, David A., "Swedish Air Force Seeks Backing for Increased Gripen Production," *Aviation Week and Space Technology*, 4 May 1987, pp. 18–21.

Bruce, Peter, "Eurofighter Cost Sparks Opposition in Bonn," *London Financial Times*, 13 August 1987, p. 2.

"Can a Plane Fly Forever?" *Newsweek*, 28 September 1987, p. 42.

"Chadwick C-122S," *Air Force Magazine*, August 1987, pp. 100–101.

Clark, Graham, "Lavi Bares its Teeth," *Military Technology*, October *86*, pp. *138–145*.

Clark, Graham, "U.S., West German Firms Team Up to Develop Highly Maneuverable Fighter," *Defense News*, 31 August 1987, p. 10.

"Claudius Dornier Seastar," *Air Force Magazine*, August 1987, pp. 102–103.

Cook, Nick, "Stormy Ride for EFA," *Jane's Defence Weekly*, 6 June 1987, pp. 1133, 1135, 1137.

Cook, Nick, "X-31A Technology Likely for EFA, ATF," *Jane's Defence Weekly*, 27 June 1987, p. 1364.

"DARPA, OSD Resurrect Faltering X-Wing R&D Effort, Craft Major New Plan," *Inside the Pentagon*, 21 August 1987, Vol. 3, No. 34, pp. 9–10.

"DARPA, USAF at Odds over Who Continues Development of Hypersonic Glide," *Inside the Pentagon*, 26 June 1987, Vol. 3, No. 26.

"Dassault and Rafale," *Aviation Week and Space Technology*, 18 May 1987, pp. 60, 62–64.

"Dassault Proposes Rafale Program with 1996 Service Introduction," *Aviation Week and Space Technology*, 20 April 1987, p. 25.

deBriganti, Giovanni, "French Companies Form Joint Venture for Rafale," *Defense News*, 16 February 1987, pp. 1, 6.

Donne, Michael, "Airship Industries Fight to Save $170M Contract," *London Financial Times*, 17 December 1987, p. 10.

"EH-101 Prototype Completes First Flight," *Aviation Week and Space Technology*, 19 October 1987, p. 31.

Eisenstadt, Steven, "Heavier Lavi Fighter Faces More Modification," *Defense News*, 2 February 1987, p. 14.

"Eurofighter, Panavia Explore Restructuring of EFA Program," *Aviation Week and Space Technology*, 29 June 1987, p. 65.

Fink, Donald E., "Israel Renews Debate on Lavi Development," *Aviation Week and Space Technology*, 1 June 1987, pp. 18–19.

"First X-29A Aircraft To Begin Performance Investigation Flights," *Aviation Week and Space Technology*, 20 April 1987, p. 60.

Fume, Wolfgang, "Helicopters as Weapons Carriers," *Military Technology*, July 1985, pp. 72–74.

"GD Puts Forward $600m F-16 Upgrade," *Jane's Defence Weekly*, 8 August 1987, pp. 218–219.

Gething, Michael J., "Lavi—The Aircraft," *Defense*, February 1987, p. 68.

Gething, Michael J., Roy Braybrook, Alexandra Schwartzbrod, and Lars Christiansson, "Return of the Dogfighter," *Defense*, July 1987, pp. 415–421.

Gilmartin, Trish, "NASA, Pentagon Set to Narrow Field of National Aerospace Plane Bidders," *Defense News*, 5 October 1987, p. 11.

Gilmartin, Trish, "Boeing, Lockheed Edged Out of NASP Bidding," *Defense News*, 12 October 1987, p. 14.

Gilmartin, Trish, "Unseeded Rocketdyne Wins Big with X-30 Bid," *Defense News*, 31 August 1987, pp. 3, 27.

"Gloves Off," *Military Technology*, October 1986, pp. 145–147.

Goodman, Glenn W., "Grumman A-6F Aircraft Debuts," *Armed Forces Journal International*, September 1987, p. 24.

Granot, Oded, "Israel Stalls Lavi Fighter Decision," *Defense News*, 16 February 1987, p. 6.

Granot, Oded, "One Eve of Crucial Vote, Israeli Cabinet Remained Split on Lavi Program's Fate," *Defense News*, 17 August 1987, p. 7.

Grimes, Vincent P., "Osprey: A Look to the Future?" *National Defense*, July–August 1987, pp. 35–40.

"Grumman's Full-Scale Development A-6F Makes First Flight at New York Facility," *Aviation Week and Space Technology*, 31 August 1987, p. 24.

Hewish, Mark, "Sweden's Air Force Modernizing for the 1990s," *International Defense Review*, July 1987, pp. 901–903.

Holland, Steve, "French Approve Rafale Attempt to Boost Exports," *Armed Forces Journal International*, August 1987, p. 48.

"JAS39 Rollout," *International Defense Review*, June 1987, p. 713.

"The Lavi Fighter," *Aviation Week and Space Technology*, Special Advertising Section, 1 June 1987, pp. 50, 53–54, 56–58, 60, 65–70, 72–74.

Lopez, Ramon L., "Bromon Bids for Military Airlifter Program," *International Defense Review*, August 1987, p. 1069.

Lorell, Mark A., *The Use of Prototypes in Selected Foreign Fighter Aircraft Development Programs,* RAND, R-3687-P&L, September 1989.

"LTV Gains A-7 Upgrade Prototype Award," *Armed Forces Journal International*, June 1987, p. 28.

Mordoff, Keith F., "Funding Delays Continue to Plague EFA Development," *Aviation Week and Space Technology*, 24 August 1987, p. 29.

Morrocco, John D., "Lockheed ATF Team Cites Lessons Learned in Prototyping Effort," *Aviation Week and Space Technology*, November 5, 1990.

Morrocco, John D., "General Dynamics Proposes F-16 Upgrade for 1990s," *Aviation Week and Space Technology*, 3 August 1987, pp. 22–23.

"National Aero-Space Plane," *Air Force Magazine*, August 1987, p. 104.

Nativi, Andrea, "AM-X: A 'Dedicated Attack Aircraft' for the '90s," *Military Technology*, July 1985, pp. 14–24.

"Navy: A-6 Upgrade Plan Will Hike Survivability, Is Key to Carrier Force Beyond 2000," *Inside the Pentagon*, 14 August 1987, pp. 6–7.

Nelms, Douglas, "McDonnell Douglas Gets NOTAR Going," *National Defense*, July–August 1987, pp. 30, 33.

"NOTAR May Be Applied to LHX Programme," *Jane's Defence Weekly*, 6 June 1987, p. 1114.

Pearce, Michael A., *Prototyping: A Strategy for the Acquisition of Naval Aircraft*, Defense Systems Management College, 10 November 1976.

"Program Delays Spur NASA, DARPA to Restructure X-Wing Flights Tests," *Aviation Week and Space Technology*, 31 August 1987, pp. 23–24.

"Rafale Completes Initial Aircraft Carrier Approach Tests," *Aviation Week and Space Technology*, 18 May 1987, p. 20.

Revellin-Falcoz, Bruno (interview), "From the RAFALE to the ACT," *Military Technology*, 1986, Vol. 3, pp. 40–42, 45.

"RNZAF to Begin Flight Testing Skyhawks Fitted with NAS," *Jane's Defence Weekly*, 8 August 1987, p. 220.

"Rockwell International/MBB X-31A EFM," *Air Force Magazine*, August 1987, pp. 99–100.

"Rockwell Wins OK to Design Jet Fighter," *Journal of Commerce*, 1 September 1987, pp. 1, 3.

Rudney, Robert and Scott D. Dean, "French Navy Walks Plank over Chirac's Rafale Endorsement," *Armed Forces Journal International*, August 1987, p. 48.

"Second Hawk Prototype Prepares for Paris Show Appearance," *Aviation Week and Space Technology*, 11 May 1987, p. 32.

"Second Lavi Fighter Prototype Enters Flight Text Program," *Aviation Week and Space Technology*, 20 April 1987, pp. 58–59.

"Skytrader Developes Light Utility STOL Transport for Military Use," *Aviation Week and Space Technology*, 6 April 1987, p. 27.

Sweetman, Bill, "Updating Older Aircraft: A View From the USA," *International Defense Review*, February 1987, pp. 151–152, 155–156.

Sweetman, Bill (with inputs from Mark Hewish and Greg Waskul), "Against the Odds: Air-to-Air Combat in the 1990s," *International Defense Review*, May 1987, Vol. 20, pp. 581–583, 586–588.

"Technological Problems, Rising Costs Force X-Wing Program to Scale Down," *Aviation Week and Space Technology*, 19 October 1987, p. 23.

"Technology, Transport Aircraft Mix," *Defense News*, 25 January 1988, p. 2.

"Transport Aircraft," *Jane's Defence Weekly*, February 1987, p. 66.

"Two Prototypes of the Aerospatiale Panther Helicopter Have So Far Been Built," *International Defense Review*, August 1987, p. 1060.

"U.S. Navy's New E-6A Communication Aircraft," *International Defense Review*, February 1987, p. 136.

Vartabedian, Ralph, "Competition for Aerospace Plane to Narrow," *Los Angeles Times*, 5 October 1987, Sec. IV, pp. 1, 2.

Vartabedian, Ralph, "Rockwell, McDonnell and General Dynamics to Vie for Aerospace Plane Design," *Los Angeles Times*, 8 October 1987, Sec. IV, pp. 1, 15.

Vartabedian, Ralph, "Voyager Designer Unveils New Double-Winged Military Plane," *Los Angeles Times*, 21 January 1988, Sec. V, p. 1.

Walker, Karen, "NH 90 Gets Green Light on Project Definition Phase," *Jane's Defence Weekly*, 25 July 1987, pp. 134–135.

"Westinghouse-Airship Wins Contract," *Jane's Defence Weekly*, 13 June 1987, p. 1165.

"X-29 Will Be Modified for High-Angle-of-Attack Flight Tests," *Jane's Defence Weekly*, 15 August 1987, p. 255.

"The X-Wing: Exciting, but Unaffordable," *Defense News*, 31 August 1987, p. 16.

"X-Wing Tests," *Jane's Defence Weekly*, 27 June 1987, p. 1369.

Young, Susan, "Gallery of USAF Weapons," *Air Force Magazine*, May 1986, p. 145.

Young, Susan H., and John W. R. Taylor, eds., "Gallery of USAF Weapons," *Air Force Magazine*, May 1987, pp. 169–186.

LAND VEHICLES (INCLUDING AIR DEFENSE MISSILE/GUN SYSTEMS):

"Air Defense LAV Variant for the USMC," *Military Technology*, October 1986, p. 249.

"Brazil's Ogum," *Jane's Defence Weekly*, 1 August 1987, pp. 189–190.

"Building Block Robotic System," *Jane's Defence Weekly*, 8 August 1987, p. 242.

Donnelly, Tom, "Army Eyes Antitank Robot," *Defense News*.

Donnelly, Tom, "BMY Appears Set to Win Army Tank Recovery Vehicle Award," *Defense News*, 10 August 1987, p. 10.

Donnelly, Tom, "BMY Counters General Dynamics' Lobbying Efforts in Tank Recovery Squabble," *Defense News*, 24 August 1987, p. 29.

"Egyptian Modernization," *Aviation Weekly and Space Technology*, 16 July 1984, p. 27.

"Ferret Computer-Aided Detection System," *Jane's Defence Weekly*, 8 August 1987, p. 242.

"First Prototype of Upgraded M44," *Jane's Defence Weekly*, 11 April 1987.

Flume, Wolfgang, "Landpower at AUSA," *Military Technology*, January 1985, pp. 49–51.

"FMC Shows Prototype AGVT Demonstrator," *Jane's Defence Weekly*, 29 November 1986, p. 1304.

Foss, Christopher F., "Latest Versions of the Light Armored Vehicle," *Jane's Defence Weekly*, 9 August 1986, p. 191.

"French Leclerc Tank," *National Defense*, July/August 1987, p. 34.

Gourley, Scott R., "U.S. National Guard to Upgrade M60A3," *Jane's Defence Weekly*, 27 June 1987, p. 1379.

"Italian MBT Makes Debut," *International Defense Review*, July 1987, pp. 857–858.

Leopold, George, "DoD Program Yields Progress for Three Autonomous Systems," *Defense News*, 12 October 1987, p. 30.

"New Information on France's Latest MBT," *International Defense Review*, March 1987, pp. 267–268.

"NFV-1 IFV Shown at ASIANDEX '86," *Jane's Defence Weekly*, 19 November 1986, p. 1304.

Ogorkiewicz, R.M., "MCV80, The New British Infantry Combat Vehicle," *International Defense Review*, June 1982, pp. 721–726.

"OTO Melara Completes First VCC-80 for Italian Army," *Jane's Defence Weekly*, 30 May 1987.

Pengelley, Rupert, "Bull Launches New Howitzers," *International Defense Review*, February 1987, pp. 169–170.

Pengelley, Rupert, "HEL's New Howitzer Testbed," *International Defense Review*, March 1987, pp. 345–349.

Pengelley, Rupert, "ISAS Heralds Hands-Off Howitzers," *International Defense Review*, April 1987, pp. 425–426.

Pengelley, Rupert, "Preparing the M109 for the 21st Century," *International Defense Review*, February 1987, pp. 173–176.

Pengelley, Rupert, "Proven Components Pay Off for Puma," *Armour 1987*, IDR Supplement, July 1987, pp. 29–31.

"Progress on GT601 Gas Turbine Engine," *Jane's Defence Weekly*, 29 November 1986, p. 1304.

"RO and BMY Shoot it Out for Egyptian Order," *Jane's Defence Weekly*, 11 April 1987.

"Robotic Ranger—Anti-Tank Weapon," *Jane's Defence Weekly*, 3 November 1984, p. 781.

Schemmer, Benjamin F, "Army Decides to Push for Light Tank, Reviving Canceled Armored Gun System," *Armed Forces Journal International*, August 1987, pp. 24, 26.

"76mm SP Anti-Aircraft Gun," *International Defense Review*, August 1987, p. 1053.

"Support Weapons Shows MF30 Automatic Cannon," *Jane's Defence Weekly*, 9 August 1986, p. 191.

"Trends-Tank Combat Weight," *Armour*, IDR Supplement, July 1987.

Turbe, Gerard, "Leclerc: A Third-Generation Battle Tank," *International Defense Review*, June 1987, pp. 759–760.

MISSILES

"ADATS Program Update," *International Defense Review*, November 1984, p. 1691.

"Army Missile Test Demonstrates FLAGE Guidance," *Aviation Week and Space Technology*, 1 June 1987, pp. 22–23.

"BAe Tracked Rapiers for U.S. Army Trials," *Jane's Defence Weekly*, 11 July 1987, p. 47.

Beyers, Dan, "Congressional Staff Report Seeks Joint Development of Navy, Air Force Missiles," *Defense News*, 26 October 1987, p. 3.

"Boeing Aerospace Displays Avenger on General Hummer HMMWV Chassis," *Jane's Defence Weekly*, 31 August 1985, p. 392.

"Close-Up on the Liberty Air Defense System," *Jane's Defence Weekly*, 11 July 1987, p. 47.

Donnelly, Tom, "Boeing System Gets Nod in Pedestal-Mounted Stinger Contest," *Defense News*, 31 August 1987, p. 12.

Donnelly, Tom, "DARPA, Navy to Build Antitank Weapon," *Defense News*, 9 November 1987, pp. 1, 35.

Goodman, Glenn W., Jr., "Army Air Defense Shoot-Out Under Way," August 1987, p. 22.

Goodman, Glenn W., Jr., "Joint Hypervelocity Missile Tests Near: Potential Low-Cost Tank-Killer of 1990s," *Air Forces Journal International*, September 1987, pp. 23–24.

"High-Speed Anti-Radiation Missile (HARM)," *DMS Market Intelligence Report*, October 1986.

"Honeywell Hits Snags in Work on Torpedo," *Wall Street Journal*, 25 September 1987, pp. 4, 6.

Lopez, Ramon, "Forward Air Defense Shoot-Off," *International Defense Review*, August 1987, p. 996.

Polsky, Debra, "Army Set to Revise FOG-M Program to Include Wider Applications of Technology," *Defense News*, 25 January 1988, p. 11.

"Trident II (D-5)," *International Defense Review*, April 1987, p. 34.

"Two Improved ADATS Systems for Trials," *Jane's Defence Weekly*, 11 July 1987, p. 48.

"U.S. Army FLAGE Missile Proves Highly Accurate," *Jane's Defence Weekly*, 6 June 1987, p. 1109.

Wooster, Captain H. Keith, Jr., "Pedestal-Mounted Stinger," *Air Defense Artillery*, Summer 1986, pp. 15–19.

ODDS AND ENDS: SHIPS AND SUBS, SUBSYSTEMS, C^3I

"Advanced Combat Rifle (ACR)," *Army*, October 1983, p. 303.

"Advanced Combat Rifle (ACR)," *Army*, October 1984, pp. 342–343.

Beyers, Dan, "U.S. Slates $5 Billion for New Engines," *Defense News*, 9 November 1987, pp. 1, 34.

Burns, Bruce P. and Richard D. Kirkendall, "BRL Improves Technology for Projectile Performance," *Army Research, Development and Acquisition Magazine*, September/October 1982, p. 18.

"Close-Assault Weapons System (CA-WS)," *Army*, October 1983, p. 304.

"Close-Assault Weapons System (CA-WS)," *Army*, October 1984, p. 346.

Cook, Nick, "Extra Boost in Sales Success for GE F404," *Jane's Defence Weekly*, 6 June 1987, p. 1116.

"Firm Proposes Apache System," *Defense Week*, 2 November 1987, p. 11.

"First Altitude Tests for Joint Technology Engine," *Jane's Defence Weekly*, 4 July 1987, p. 1458.

"First Flights for New Generation Fighter Radar," *Jane's Defence Weekly*, 18 July 1987, p. 82.

Gleick, James, "New Frontiers of Communication Lie in Superconductor Test Device," *New York Times*, 2 October 1987, p. 1.

"Hughes Group Wins ATF Avionics Contract," *Aviation Week and Space Technology*, 3 August 1987, p. 32.

Leopold, George, "GE, Martin Team on IRST System," *Defense News*, 31 August 1987, p. 13.

Leopold, George, "Technology Enhances Target Recognition," *Defense News*, 5 October 1987, pp. 1, 45.

Marshall, Rick, "France's Thomson Plans a U.S. Market Strategy," *Defense and Foreign Affairs*, November 1986, pp. 34–35.

"McDonnell Douglas F-15E Continues Testing," *International Defense Review*, March 1987, p. 270.

"McDonnell Douglas Resumes Flight Tests with GE UDF Engine," *Aviation Week and Space Technology*, 2 November 1987, p. 35.

"Prototype GIAT 105 LG1 Gun," *Jane's Defence Weekly*, 8 August 1987, p. 229.

"Prototype Sub: One-Half the Size, Two-Times the Lethality, Speed of Current Subs," *Inside the Pentagon*, 31 July 1987, p. 7.

Rhea, John, "The U.S. MIMIC Program: A Complement to VHSIC in Smart Weapons," *International Defense Review*, May 1986, pp. 669–670.

Salvy, Robert, "Thomson-CSF's New RDY Combat Aircraft Radar," *International Defense Review*, August 1987, pp. 1065–1066.

"SDIO to Conduct Hypervelocity Firing of Subscale Thunderbolt Prototype," *Aviation Week and Space Technology*, 24 August 1987.

Silver, Howard, "U.S. Working on Warheads to Hit Soviet Underground," *Omaha World-Herald*, 27 September 1987, pp. 1, 10.

Sweetman, Bill, "The New Wave in Aircraft Power," *International Defense Review*, June 1987, pp. 765–770.

Sweetman, Bill, "U.S. Trends in Helicopter Propulsion," *International Defense Review*, January 1987, pp. 49–54.

"USA Plans Revolutionary Nuclear Submarine Design," *Jane's Defence Weekly*, 27 June 1987, p. 1345.