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**THE COSTS AND RISKS OF MATURING TECHNOLOGIES, TRADITIONAL VS. EVOLUTIONARY APPROACHES**

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**by**

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# The Costs and Risks of Maturing Technologies, Traditional vs. Evolutionary Approaches

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## Abstract

Evolutionary acquisition holds the potential to improve both the cost of defense acquisition and the performance of acquired systems. Traditional acquisition programs tend to employ promising, yet immature, technologies and develop them within the program. Because immature technologies are inherently risky, unforeseen obstacles to development can lead to substantial cost overruns and schedule delays. This results in

infrequent, but large, increments of deployed capability. In contrast, evolutionary acquisition employs more mature, less-risky technologies. This results in more frequent, smaller increments of deployed capability. In theory, evolutionary acquisition could be more cost effective than traditional acquisition approaches because it avoids most of the risk inherent to technology development. However, there is a latent issue regarding evolutionary acquisition. If technology is not matured within a program, it must be matured somewhere else. For critical, DoD-specific technologies, this cost must logically fall on the DoD itself. The question, then, is whether it is more cost effective to mature technologies within the R&D system or within an acquisition program? A simulation of the defense acquisition system is developed to address this question.

## 1. Introduction

Over the past several years, the United States Department of Defense (DoD) has been attempting to transform itself from an organization designed to meet the Cold War threat of the Soviet Union to a more flexible, adaptable organization that is ready to meet the regional and asymmetric threats the US expects to face in the coming years. To facilitate this transformation, several modifications have been made to the defense acquisition system—the most important being the shift to evolutionary acquisition.

Evolutionary acquisition is an attempt to address one of the most common criticisms of the defense acquisition system. Traditional acquisition programs attempt large, revolutionary leaps in system capability through the use of immature and risky technology. Not only does immature technology often require more time and money to develop, but it also introduces uncertainty that may lead to significant delays and cost overruns. Consequently, warfighters must often make due with increasingly obsolete equipment during the long intervals between new system deployments, and there is little flexibility to adapt to emerging threats and exploit technology opportunities.

Evolutionary acquisition, on the other hand, attempts to set more modest capability goals for each acquisition. The idea is to use more mature, and hence, less-risky technology, in order to shorten acquisition cycle-times. Thus, each acquisition cycle under evolutionary acquisition should be shorter and cost less than more traditional programs. As a result, warfighters should receive more frequent upgrades to their equipment and, thus, should be at less risk of going to war with obsolete hardware.

Despite the apparent motivation to implement evolutionary acquisition and committing the approach to policy, it would seem that the DoD has had limited success in doing so (Lorell, Lowell & Younossi, 2006). In fact, the US Government Accountability Office (GAO) has suggested that DoD reforms have not gone far enough (GAO 2003; 2006, September; 2006, April; 2007a). They advocate adapting commercial best practices regarding technology and product development to the defense acquisition system. Among these are a centralized portfolio approach to managing new systems and technologies, a staged knowledge-based approach to both acquisition and technology development, strict enforcement of technology maturity requirements, and a more evolutionary approach to new system development.

Since these reforms are derived from the commercial world, the obvious question is whether they will translate well to a government context. The defense acquisition system differs from a commercial product development process in several respects. In particular, the government essentially serves as a technology developer, system developer, customer, and user. Furthermore, the DoD and a few allies are really the only customers for the systems and technologies developed within the defense acquisition system. Thus, there is a more limited capacity to purchase multiple evolutionary iterations of a system than there would be with a consumer product. Consequently, the pertinent question is, if evolutionary acquisition were fully implemented, would there be any tangible benefit for the Department of Defense? Since evolutionary acquisition is inseparable from technology policy, the objective of this paper is to consider the implications of an evolutionary technology policy on the cost and performance of the defense acquisition system.

As a first step to better understanding the system level trade-offs of technology policy on acquisition, the work presented in this paper attempts to model the basic "physics" of the acquisition system, in particular, the relationship between the R&D process and the acquisition lifecycle. The purpose is to gain insight into the most fundamental system-level influences on the efficacy of acquisition policies. To that end, an idealized view of the acquisition system is adopted to which complicating factors may be subsequently added to test their effects. The acquisition model was implemented as a discrete event simulation with the key decision variable being the maturity level at which a technology moves from R&D to an acquisition effort. Extensive sensitivity analyses were performed and several insights into the impact of technology policy on acquisition were generated. The most important output of this effort, however, is an informed set of future research directions that will facilitate more definitive answers to major policy questions regarding evolutionary acquisition. What follows is a summary of key findings. For a more detailed discussion of the analysis approach and results see Pennock (2008).

## 2. Background

As was mentioned previously, evolutionary acquisition is an attempt to reduce acquisition cycle-times by setting capability goals that are more modest than is typical of a traditional program. This allows programs to utilize more mature technology and, hence, reduce the amount of technology risk. In theory, this should reduce cost, schedule, and performance uncertainty. The hope is that it will lead to less-expensive acquisition programs that proceed more quickly. Consequently, warfighters would receive up-to-date equipment more frequently and at lower cost.

The motivating issue behind evolutionary acquisition is cycle-time. In theory, shorter cycles mean that each is less expensive and new technologies can be moved into the field faster to meet emerging warfighter needs. The driving issue, then, is how big of a leap in capability should one attempt during each acquisition cycle? Of course, the risk associated with the size of the leap is linked to the maturity of the required technology. Thus, evolutionary acquisition is really all about technology policy because with a large enough leap, evolutionary becomes revolutionary.

So where does the DoD's approach to evolutionary acquisition come in? A key issue is that the DoD does not manage technology or "product" portfolios in the same manner as a large commercial enterprise. In part, this is due the public nature of the defense enterprise. Even so, the GAO asserts that the DoD should adopt additional commercial best practices regarding the centralized management of its acquisition and technology portfolios and the management of technology transitions from R&D to acquisition programs (GAO, 2006, September; 2007a). Under the current system, there is often a funding gap in technology development. Early-stage technologies are funded through the R&D system (or S&T as it is known in the DoD), and late-stage technologies are often funded in support of a particular acquisition effort. It is technologies in the middle stages of maturation that are often left without obvious ownership and hence funding. Consequently, if certain technologies are required by an acquisition effort, their development through the middle stages must be funded in support of the development of a particular system. This requires early commitment to a technology when its final realization is still uncertain. In the past, this has often led to disappointment as technologies took longer to develop and did not perform as well as expected. In fact, a recent National Research Council report suggests that concept decisions made prior to Milestone A determine 70-75% of lifecycle costs (NRC, 2008). Early commitment to system concepts that depend on immature technologies sacrifices flexibility and may lead to costly rework.

Theoretically, if the DoD adopted the commercial new product model that the GAO suggests (GAO, 2006, September; 2007a), it would allow the DoD greater flexibility in how to select and mature technologies for development in anticipation of future acquisition program needs. In essence, it would lead to the creation of additional technology options. This would reduce the burden and risks of technology development on acquisition programs since they could choose from a portfolio of mature technologies.

So in the end, the two fundamental questions of evolutionary acquisition are how mature should technologies be when they are transitioned from R&D to acquisition efforts, and what is the best approach to mature them? All else being equal, this essentially determines the acquisition cycle-time as well as the size of the capability improvement for each cycle. Ultimately, the answer will hinge on factors such as the cost of technology maturation, the rate of learning from fielded systems, and the overhead cost associated with an acquisition cycle.

## 3. Model Setup

The motivation behind the structure of the model is to represent the set of commercial best practices recommended by the GAO for implementation in the context of the defense acquisition system. This includes both a staged, centrally managed technology development process as well a strictly enforced acquisition program lifecycle. Given the staged nature of both R&D and acquisition, discrete event simulation was the logical choice to capture the behavior of the system. As was mentioned previously, the representation of the defense acquisition system presented here is intentionally scaled-down and idealized. The benefit of an idealized model is two-fold. First, the scaled-down representation is more tractable and allows us to attempt multiple experimental excursions. Second, it allows us to consider the structural impacts of technology policy unobscured by the inconsistent implementation that occurs in the actual defense acquisition system. In particular, the modeling emphasis was on the linkage between the movement of technologies through the R&D process to the length and cost of the acquisition cycles. In order to represent the impact of technology policy on defense acquisition, there were three key features of the system that required consideration: the movement of technologies through the R&D system, the movement of programs through the acquisition process, and the rate of technological progression.

The simulation was implemented using the Arena 10.0 software package and consists of three major components: the technology development process model, the system acquisition process model, and the technical progress model. The technology development process model describes how technologies with potential defense application are matured through the defense R&D system. This process provides a portfolio of technologies for use by acquisition programs. The system acquisition process model describes the lifecycle of a defense acquisition program from concept development to deployment. Finally, the technical progress model describes how the capabilities provided by technologies improve over time.

### 3.1 Technology Development Process Model

The technology development process model simulates the movement of individual technologies through a maturation process. Ideally, a technology development process is centrally managed and staged. Technologies are selected for development based on their potential applicability to future products. In the commercial world, product and technology roadmaps drive development. These roadmaps, and the organization's commitment to them, provide a shared vision that the DoD often lacks. However, developing the technologies to satisfy the roadmap entails a certain amount of risk. In order to mitigate that risk, each technology must pass through a series of stage-gates. Each gate provides an opportunity to evaluate the status of a technology and determine whether it should continue to receive funding. Such a system facilitates prioritization of technology projects as well as risk mitigation. It is important to note that the Department of Defense has not consistently implemented such a system (GAO, 2006, September). Instead, there are a number of different organizations throughout the DoD that perform or fund R&D work, each with its own way of managing technology projects. These inconsistencies preclude the effective management of technology development and promote duplication and mismatch between the technology supplied by R&D organizations and the technology demanded by acquisition programs. Consequently, for this study, the technology development process was modeled in the spirit of the GAO's recommendation of a centrally-managed and staged technology development process.

The process starts when new but immature technologies arrive for evaluation. The arriving technologies are prioritized and then funded until the budget is expended. Rejected technologies are considered for funding in future rounds, and successfully matured technologies move on to the next stage. The sequence repeats until each technology is either successfully matured or discarded. The maturity of each technology is measured by the Technology Readiness Level (TRL) scale. The purpose of a properly functioning technology development process is to prioritize and fund these technologies by potential cost and benefit. The process used in this simulation is represented in Figure 1. For more information see Pennock (2008).

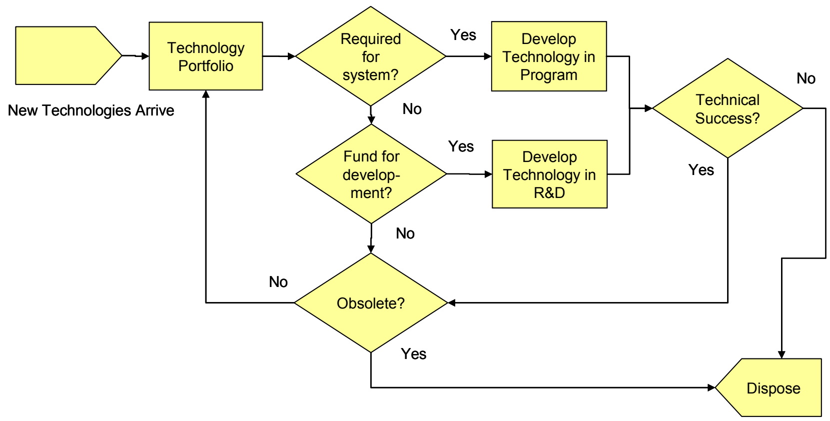


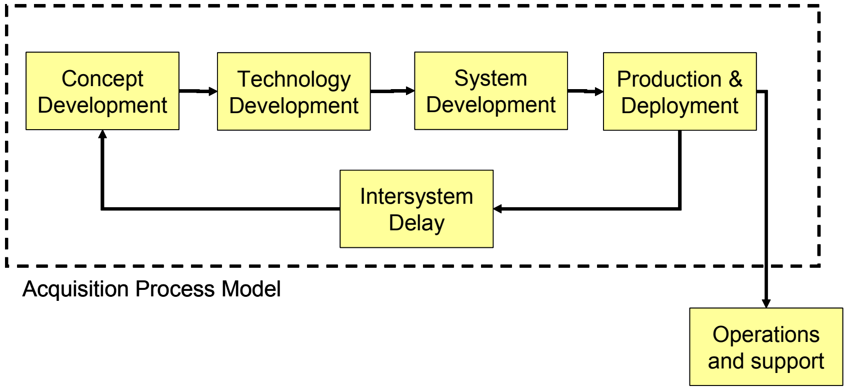

**Figure 1. The Technology Development Process Model**

## 3.2 System Acquisition Process Model

The system acquisition process model describes the lifecycle of a defense acquisition program. It is based on the five-stage Defense Acquisition Management Framework (DoD, 2006). As with the technology development process model described above, the acquisition process model in the simulation will assume that acquisition programs follow the rules, and, consequently, programs will move through each phase in order with no concurrency.

Within the simulation model, the basic unit in the system acquisition process is a program to acquire a system. It is assumed that the DoD has several types of systems. Each type is continuously cycling through the acquisition process. For example, if the Air Force deploys a new air superiority fighter, it is assumed that it will begin concept development of its replacement shortly thereafter. This assumption will be relaxed later.

Each type of system is dependent upon several technologies, each from a different application area. For example, an air superiority fighter might require a propulsion technology, a sensor technology, and an avionics technology. The acquisition process model used in the simulation is illustrated in Figure 2. For more information see Pennock (2008).




Note: Operations and Support was considered outside the scope of this simulation.

**Figure 2. The System Acquisition Process Model**

Ultimately, the purpose of acquiring a system is to provide military capabilities. It is assumed that each system deployed provides a capability. Capability in the model is an abstract representation of military utility. It is assumed that there is a synergistic effect between the technologies employed in the system: the system being greater than the sum of its parts. Thus, a multiplicative model is used to represent capability. The capability of a deployed system is the product of the performance levels for each of its required technologies. Thus, an air superiority fighter without a propulsion system is useless no matter how capable its sensor is. This measure of capability allows us to determine the cost effectiveness of a particular technology policy.

### 3.3 Technical Progress Model

The final key feature of the simulation is the model of technical progress. Where do new, more capable technologies come from? It is important to note that the technology development model in this simulation does not consider basic research. In fact, TRL 1 signifies the transition of ideas, concepts, and technologies from basic research to applied research. Thus, we can assume that there is a certain amount of research occurring exogenous to the simulation. This research may come from government or commercial sources. The key is that there is a constant inflow of new technologies and that their performance improves over time. The purpose of the technology development process is to adapt these technologies for use in a military system. There is one caveat, however, and that is that a purely exogenous technical progress model neglects the learning that inevitably occurs from fielding systems. For example, valuable information gathered from field use of a jet engine will likely inform the development of the next generation jet engine. Thus, there is a learning effect, and the more rapidly systems are fielded, the sooner subsequent learning will be available for future technologies. This is especially true for military-specific technologies in which the only source of user feedback is the military itself.

Consequently, the technical progress model in this simulation attempts to model both these features. To do so, a hybrid model was created. First, there is a baseline technology coefficient for each application area. Whenever a technology is fielded, the coefficient is multiplied by a learning factor (e.g., 1.1). This captures the learning from implementation. Second, there is an exponential growth model for each application area. This represents the learning from exogenous R&D activities. The two are multiplied together to determine the current technology level and are represented by the equation

$$Ce^{gt}$$

where *C* is the technology coefficient and *g* is the exogenous growth rate. Arriving technologies are assigned a performance as a random variation on this value. The parameters of this model can be adjusted to accommodate the specific situation of each application area. For example, technologies that are used commercially may have a high exogenous growth rate and low learning factor because their progress would continue regardless of military use. The reverse may be true for military-specific technologies since there would be little learning from commercial use.

## 4. Experimental Design

### 4.1 Simulation Parameters

As previously mentioned, the DoD has been relatively inconsistent in its implementation of its own policies, and evolutionary policies—in particular—are fairly new. Consequently, using historical data to set simulation parameters is particularly problematic. In fact, a RAND study to assess cost growth in weapon system programs found a number of issues in the available cost data for defense acquisition programs (Arena, Leonard, Murray & Younossi, 2006). Some of these issues include significant aggregation of data, baseline changes, changes in reporting guidelines, and incomplete data. The situation is worse for technology maturation. As indicated by the GAO, the DoD does not systematically track its technology development efforts (GAO, 2006, September). Furthermore, the introduction of TRL levels to the DoD is fairly recent, so there is little experience with their application in a DoD context. Since NASA has been using the TRL scale for some time, it would seemingly be a logical source of information regarding the cost and risk associated with maturing technologies through TRL levels. Unfortunately, a 2005 study at NASA to determine the cost and risk found that poor record keeping resulted in insufficient useful data to achieve statistically significant results (Kirn, 2005).

Fortunately, the aim of this study is not to precisely recreate the defense acquisition system as it is but to identify policy directions to determine how it should be. This, in combination with extensive sensitivity analysis, allows for a more reasonable margin of error in setting the simulation parameters. Consequently, the actual values used in the experiments are an amalgamation from several sources, including reports and studies from both government and commercial sources (Bodner & Rouse, 2007; DoD, 2007 April; DoD, 2007 August; Fox, 1988; GAO, 2007b; Kirn, 2005; Stevens & Burley, 1997).

### 4.2 Basic Experiment

In order to answer the research questions posed in this paper, three cases were developed. The three cases are variations on the key experimental variables, the Min TRL and the Fallback TRL. The Min TRL is the minimum maturity requirement for a technology used in an acquisition program, and the Fallback TRL is the minimum maturity selected when the first choice technology fails. The cases are as follows:

- **Base Case**—The base case most closely resembles the current modus operandi of the defense acquisition system. Technologies are selected at mid-TRL levels and final maturation occurs during the technology development phase of an acquisition effort. High performing, but immature technologies are preferred over more mature, proven technologies. If a technology fails, however, the program will fall back to a more mature technology.
    - Min TRL = 4
    - Fallback TRL = 7
- **Evolutionary Acquisition**—In this case, programs may only use fully mature technology. Maturation of technology is funded in the R&D system, and there is effectively no technology development phase. (Note that TRL 7 was chosen here because TRL levels 8 and 9 are system specific.)
    - Min TRL = 7
- **Revolutionary Acquisition**—Programs target maximum performance at all costs and, thus, always choose the technologies with the highest expected performance. When a technology fails, another top performer is selected in its place.
    - Min TRL = 4
    - Fallback TRL = 4

There are several outputs of interest. These are the cost of operating the entire acquisition system, the cost of an individual program, the annual capability growth rate, and the acquisition program length. Of course, we are interested in the long-run behavior of these outputs. Consequently, to perform the experiments, the simulation was run for a warm-up period in order to fully populate the technology portfolio, and then statistics were collected on the outputs of interest.

In particular, each simulation was run for a warm-up period of 50 years and then statistics were collected for another 150 years. There are 40 replications for each experimental case. As for the acquisition programs, there are three system types each requiring three technologies. Each of those technologies falls into one of six application areas. It was assumed that the three acquisition programs are homogenous in terms of cost and schedule risk, and it was also assumed that the application areas are homogeneous in terms of cost, schedule, and technical risk. The budget for the technology development process was set to $3 billion, and was allocated among the six stages so as to ensure a smooth flow of technologies through the system. It was also assumed that all of the stages are of equal length. This is simply to focus on the technical risk for the basic experiment. Finally, the technical progress model is identical for all six application areas and features a mix of exogenous technical progression and learning.

### 4.3 Sensitivity Analysis

The simulation developed is quite flexible and many different scenarios can be analyzed. A first order sensitivity analysis was performed, and the results are presented in Pennock (2008). It was found that the simulation outputs were particularly sensitive to five factors: the R&D budget size, the R&D budget distribution, the rate of technical learning, the technology development stage length, and production costs. The impact of the size of the R&D budget was examined by leaving the percent allocated per stage the same but varying the aggregate amount over the range of -50% to +50%. The budget distribution was analyzed by reducing the budget for stages 4, 5, and 6. This particular scenario was designed to represent the status quo of the defense technology development process. To understand the influence of the rate of technical learning, the learning factor from the technical progress model was varied between 1 (no learning) and 2. In the basic experiment, all technology development stages are one year in length. To understand the impact of stage length, the scenarios were run with stage lengths of two years and three years. Finally, the influence of production costs was analyzed by varying the cost rate from -100% to +100% of the baseline value.

## 5. Results and Analysis

### 5.1 Results of the Basic Experiment

First, we will consider the results of the basic experiment. The average values of each of the output statistics are displayed in Table 1. Note that for compactness, system specific outputs are only shown for system 1. The results are similar for the other two systems. The most obvious question is how do these program outputs compare to real acquisition programs? As far as program duration, the distributional parameters for concept development, system development, and production were derived from Fox (1988, p. 29). with an average program duration of 15 years. We see from Table 1 that the base case has an average duration of 14 years, which is fairly close. As for cost, Fox does not provide cost data, but a recent GAO report provides the cost and schedule performance of 62 current weapons system programs (GAO, 2007b). An analysis of these data reveals that the average program cost is approximately $16 billion. An important caveat is that these data cover a wide range of programs. Some are small upgrade programs that are short and inexpensive while others are major system of systems acquisitions that will take 30 years and cost hundreds of billions of dollars. Even so, we can see from Table 1 that the average program cost for the base case is approximately $16 billion. Thus, we can say that the simulation outputs are within the right order of magnitude for an “average” acquisition program.

**Table 1. The Average Output Values over 40 Repetitions for the Scenarios of the Basic Experiment**

| Output | Base Case | Evolutionary | Revolutionary |
|---|---|---|---|
| **Total Acquisition System Operating Cost** ($ million, annualized) | 5807 | 6410 | 5169 |
| **Capability Growth Rate** (System 1) | 0.16 | 0.179 | 0.138 |
| **Program Duration** (System 1, years) | 14.3 | 11.8 | 17.2 |
| **Program Cost** (System 1, $ million) | 16091 | 14668 | 16736 |

In order to understand these results fully, we will address each of the four outputs in turn. Figure 3a depicts the 95% confidence intervals for the average annual cost to operate the acquisition system. Clearly, evolutionary acquisition is the most expensive and revolutionary acquisition is the least expensive. If the technology policy is less aggressive with evolutionary acquisition, why would it be more expensive? To better understand this outcome, let us consider the average cost of the individual programs.

Figure 3b shows the confidence intervals for the average program cost to acquire a system of type 1. Here we see that the average program cost is actually lower with evolutionary acquisition than revolutionary acquisition. So as evolutionary acquisition supporters suggest, using mature technology must lower program cost. Then why does the acquisition system cost more to operate under evolutionary acquisition?

The answer is revealed when we examine the average program duration or cycle-time. In Figure 3c, we see that the program length is much shorter with evolutionary acquisition. With a shorter cycle-time, acquisitions happen more frequently. Each cycle imposes overhead costs including system development, production, and deployment costs. Since these overhead costs are far greater than any savings that would result from more efficient management of the technology portfolio, the overall cost rises.

But does the additional cost of evolutionary acquisition buy the DoD anything? Figure 3d reveals that evolutionary acquisition results in a superior annual capability growth rate. The annual capability growth rate is the “average” annual rate of capability improvement. Much like an interest rate, even small differences in the rate can result in a huge difference in the level of deployed capability over the long-run. Thus, we see that there is a cost/performance trade-off governed by the technology maturity requirement. Allowing less-mature technology hurts system performance because it takes longer to move technologies into the field, but since it incurs large production costs less often, it is also less expensive. Strictly enforcing maturity requirements, on the other hand, means shorter, less-expensive programs that achieve high performance by moving technologies into the field more quickly. Unfortunately, this incurs production costs more frequently and results in increased operating costs for the acquisition system as a whole.

In fact, by varying the technology policy we can move along a roughly linear frontier of cost/performance combinations. Figure 4 shows the cost and performance for all possible technology polices such that 1 ≤ Min TRL ≤ 7 and Fallback TRL ≥ Min TRL. At first, this result would seem to suggest that technology policy should not be strictly enforced as budgetary restrictions would force changes in technology policy to meet cost goals. Fortunately, this is not the case.

In order to maintain a consistent, evolutionary technology policy but retain the ability to trade performance for cost, all that is required is to insert a delay between acquisition cycles. Figure 5 depicts the cost/performance combinations for the evolutionary policy with inter-cycle delays ranging from 0 to 7 years. Also shown is the linear trend line from Figure 4. Clearly, the introduction of a delay allows the evolutionary policy to replicate the cost/performance combinations achieved through shifts in technology policy. Thus, for any given cost target, an efficient policy can be found by imposing the evolutionary maturity requirements in combination with the appropriate inter-acquisition cycle delay.

## 5.2 Sensitivity Results

The previous section presented the results of the basic experiment, but there remains a question of robustness. How stable are results? Are there any cases in which the evolutionary policy is not the best performing? While five scenarios were described in Section 4.3 above, due to space constraints only two will be presented here. For the remainder see Pennock (2008).

First, we consider the distribution of the R&D budget among the stages. In particular, this scenario is designed to represent a situation that is often referred to as crossing the chasm. Crossing the chasm describes the difficulty that technology development efforts often encounter in moving through the middle stages of technology maturation because of a scarcity of funding. To simulate this scenario, funding for stages 4, 5, and 6 was varied over a range of 25% to 100% of the baseline value. Figure 6 reveals that the best policy from a performance standpoint is quite sensitive to the level of middle-stage funding.

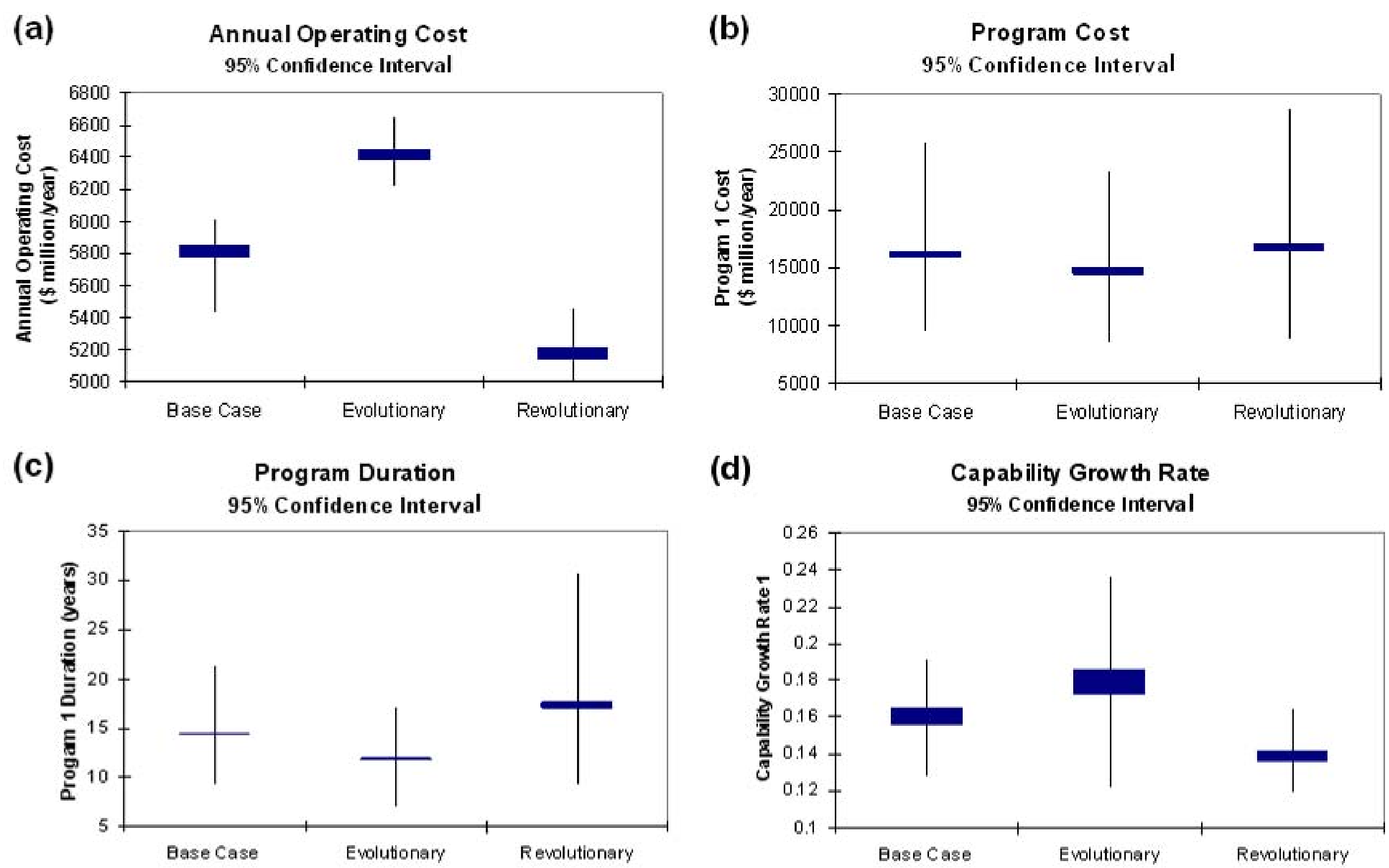



**Figure 3. 95% Confidence Intervals by Scenario for the Mean Values of Each of the Four Primary Outputs**

**Note:** The height of the box represents the width of the confidence interval, and the vertical lines represent the range of realized values.

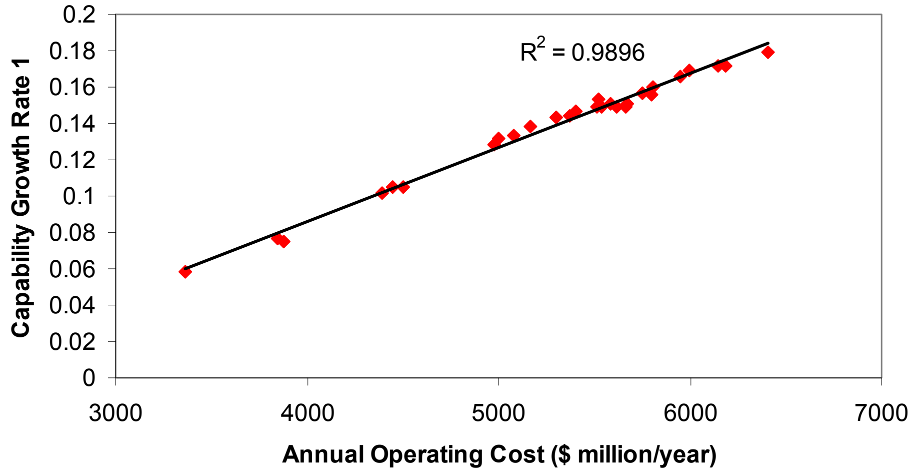



**Figure 4. Cost/Performance Trade-off for All Possible Technology Policies with a Linear Trend Line**

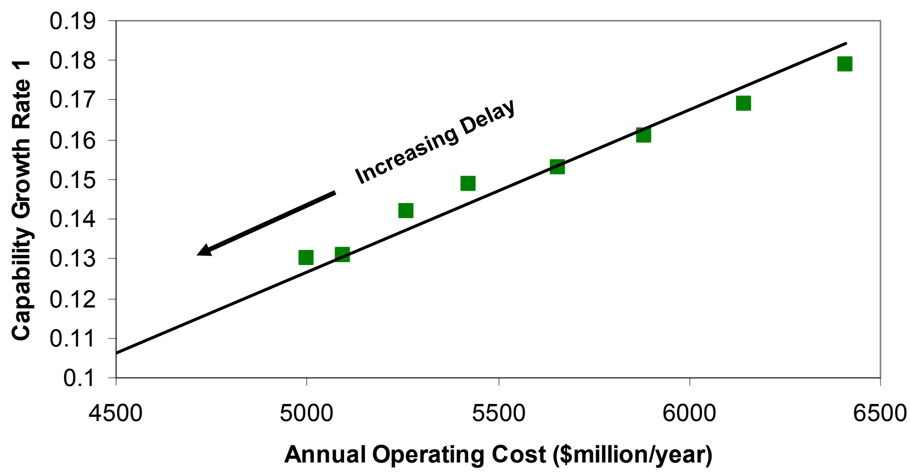



**Figure 5. Cost/Performance Trade-off Replicated through the Evolutionary Policy with an Inter-cycle Delay**

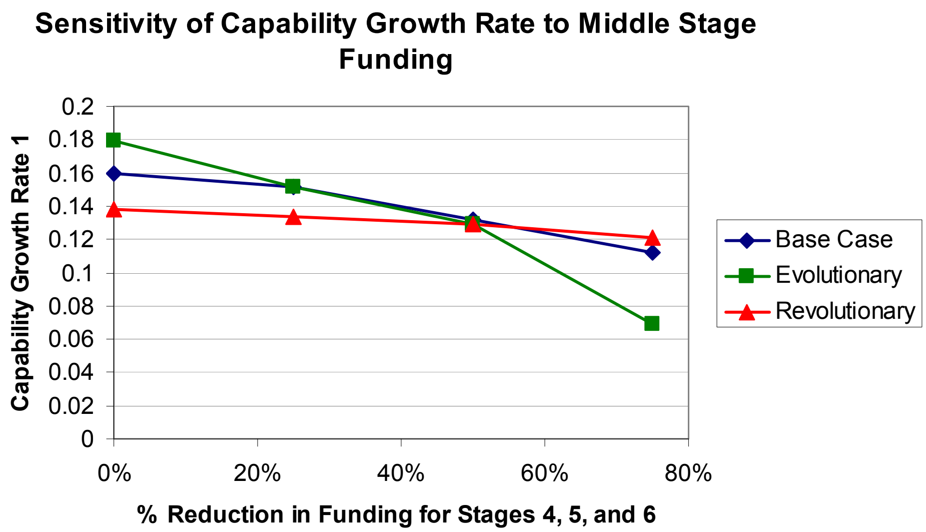



**Figure 6. Capability Growth Rate when Middle-stage R&D Funding Is Cut**

As we would expect, the evolutionary policy is the most sensitive since it is dependent upon a constant supply of mature technologies. On the opposite end, the revolutionary policy is the most robust since it can provide its own middle-stage funding, and once again, the base case falls in between. Given the varied rates of performance decay among the three policies, there are domains in which each is dominant. When R&D is well funded, the evolutionary policy provides superior performance. As middle-stage funding is reduced by more than 25%, the performance of the base case policy begins to exceed the performance of the evolutionary policy. As funding declines further, the revolutionary policy becomes the top performing policy.

Of all of the scenarios presented in this paper, the crossing the chasm scenario is probably the most similar to business as usual at the DoD. Typically, S&T funding covers early-stage technology development, but once technologies reach the middle stages, the only readily available source of funding is through an acquisition effort. The base case policy is also fairly similar to the risk mitigation strategy that many acquisition programs use: try to utilize the most promising technology, but if that fails, fall back to the existing, mature technology. Thus, it would seem that given the circumstances that most acquisition programs operate under, the business as usual policy is quite rational. Of course, it should be pointed out that all of the acquisition policies perform better when middle-stage R&D is well funded.

The final scenario represents the impact of production costs on the affordability of evolutionary acquisition. The production cost rate was varied from zero to $8 billion per year. Figure 7 reveals that as procurement cost increases, the spread between the operating costs of the three policies increases. The shorter the acquisition cycle, the more frequently production costs are incurred and, consequently, the greater the impact of an increase in production costs. Conversely, the lower production costs are, the more cost effective evolutionary acquisition becomes.

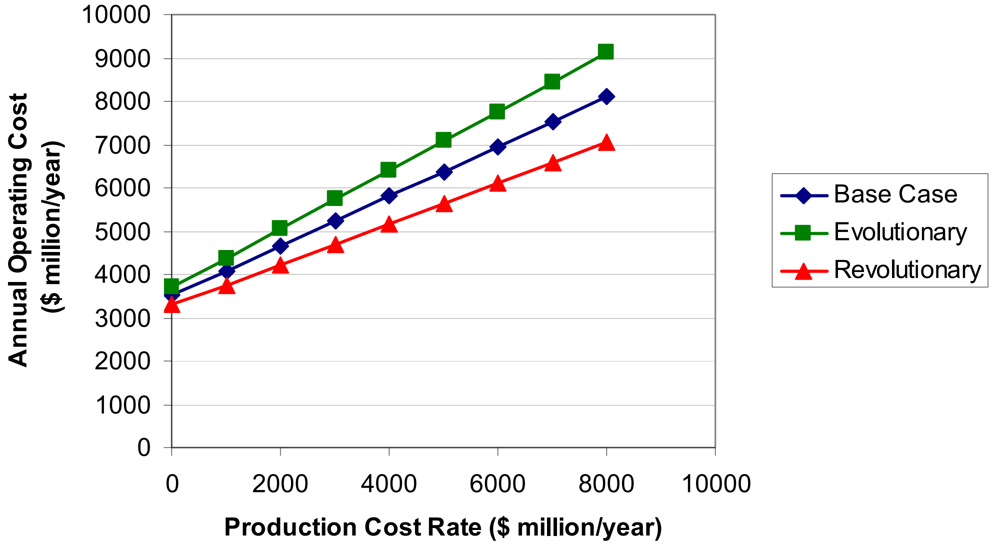



**Figure 7. The Annual Acquisition System Operating Cost as a Function of the Production Cost Rate**

## 6. Discussion

The production cost scenario raises several issues regarding evolutionary acquisition. Clearly, the more expensive it is to produce and deploy the next iteration of a system, the less affordable evolutionary acquisition becomes. But, of course, that is dependent upon the nature of the system under consideration, and this is a key difference between evolutionary practices in a commercial setting versus a defense setting. A commercial firm does not purchase its own product. In fact, if we take the example of a car manufacturer—there is always a substantial portion of the customer base that is looking to buy a new car. Thus, the car manufacturer is going to build and sell cars continuously. The costs of upgrading a model might include the costs of any technology development, the cost of changing the design, and the cost of any retooling that must be done at production facilities. If the manufacturer is particularly successful, it may gain market share from its competitors, and thus, the investment pays for itself. Consequently, a commercial firm can actually make more money from cycling faster and using an evolutionary approach. When the DoD would like to buy a new weapon system, it must pay for all of the same development costs and purchase the product. Furthermore, if through more rapid acquisition cycles the DoD improves the performance growth rate of its systems, it may outperform its adversaries, but it does not generate a monetary return to help fund the faster pace of system development.

Thus, the cost of evolutionary acquisition is critically dependent upon the length and cost of stages in the system acquisition lifecycle. The simulation model presented in this paper was generic in the sense that it assumed that something was acquired in each cycle, but it did not differentiate between a new system design or a product upgrade. Representing either case could be achieved by simply changing the cost and duration parameters in the model. The key outcome of the evolutionary policy was that simply employing mature technology shortened the acquisition cycle and reduced the cost of each cycle. In the examples above, however, the decline in cycle costs from more efficient technology development alone was not sufficient to compensate for the increase in the cycle rate. Thus, total acquisition costs rose with evolutionary acquisition. Some have suggested, however, that the length and cost of other phases of the acquisition lifecycle would decline under evolutionary acquisition as well. The idea is that if acquisition programs are less ambitious and shorter, development will be easier and there will be fewer problems with unstable funding.  Thus, we should expect lower system development and procurement costs as well.  Consequently, the question becomes, if the costs of system development and production decline under evolutionary acquisition, does evolutionary acquisition then become less expensive than more traditional methods?

To consider this question let us develop a very simple model for the cost of operating the defense acquisition system. First, we define the following symbols:

- $r_{ij}$ ≡ the acquisition cycle rate for system *i* under policy *j* in cycles per year.
- $C_{ij}$ ≡ the cost per acquisition cycle for system *i* under policy *j*.
- $K_j$ ≡ the total cost per year for operating the defense R&D system under policy *j*.
- $A_j$ ≡ the annual cost of operating the defense acquisition system under policy *j*.

We can define the cost rate to operate the acquisition system under policy *j* as

$$A_j = \sum_{i=1}^{n} r_{ij} C_{ij} + K_j$$

where *n* is the number of systems begin acquired.  Thus, if policy *e* represents evolutionary acquisition and policy *t* represents traditional acquisition, then evolutionary acquisition would be less expensive if $A_e < A_t$.  For the moment, let us assume that all systems being acquired have identical cost and cycle rates. This leaves us with the relationship

$$n r_e C_e + K_e < n r_t C_t + K_t.$$

Furthermore, if we assume that we keep our R&D budget fixed we can simplify even further to yield

$$\frac{C_e}{C_t} < \frac{r_t}{r_e}.$$

Of course, since the rate of acquisition is slower under the traditional acquisition policy, the right-hand side will be strictly less than one.  This implies that a simple decline in program costs from evolutionary acquisition is not sufficient to reduce the total cost to operate the acquisition system.  Instead, program costs must decline sufficiently to offset the increase in the rate of acquisition.

To better illustrate this point, imagine that acquisition cycles were weekly and cost $10. The operating cost would be $10 per week.  Now let us assume that we institute a new policy that reduces cycle costs to $8 per cycle, but the cycles now occur twice as fast.  That means that under the new policy, the operating cost would be $16 per week.  Thus, even though the cost per cycle decreased, the total cost increased.

When we consider defense acquisition cycles, if the system development and procurement costs also drop under evolutionary acquisition, it might seem to suggest that we could overcome this deficit. If, however, the durations of system development and technology development also decrease, then the equivalent cost threshold becomes even more difficult to reach. Furthermore, if we consider spiral development when there are several short, overlapping cycles, we see that we would require fairly low development, production, and deployment costs to compensate for the speed of the cycles.

Thus, the critical question becomes, how does evolutionary acquisition affect the length and cost of development and procurement activities versus a traditional single-step to capability approach? This is not a trivial question, and the answer will likely depend on the type of system being acquired. Upgrades to complex, integrated systems can lead to substantial design modifications to accommodate even seemingly simple changes and using more mature technologies does not correlate to easier integration (Smaling & de Weck, 2007). In fact, experiences at Westland Helicopters indicate that even when a system such as a military helicopter is designed with modularity and upgradeability in mind, changes can unexpectedly propagate through large portions of the system design (Clarkson, Simons & Eckert, 2004; Eckert, Clarkson & Zanker, 2004). At the other end of the spectrum, systems with very loose coupling between system components may be quite amenable to rapid upgrade and change. Perhaps the most extreme example of this type of system is the Internet, in which the system architecture changes continuously without any supervision or control.

Thus, this issue merits substantial additional research and is really the determining factor regarding evolutionary acquisition's potential for cost savings. This is not to suggest that if the costs of acquiring a particular system type do not decline under evolutionary acquisition that the approach is useless. The results of this study suggest that evolutionary acquisition delivers other benefits such as a boost in the capability of systems actually deployed in the field. Instead, it simply means that additional capability will continue to come at additional cost. Consequently, cost and performance may be traded off by simply, appropriately spacing acquisition cycles.

## 7. Conclusions and Further Research

The results from this simulation study lead to some highly suggestive findings and critical avenues for future research. First and foremost, with a first-order representation of the acquisition system, the results suggest that the adoption of evolutionary acquisition policies has the potential to improve the performance of deployed systems. However, lower operating costs for the defense acquisition system are not automatic. While each individual program should be less expensive under evolutionary acquisition policies, the faster acquisition cycle-time means that development, production, and deployment costs are incurred more frequently. This may overwhelm any cost savings from managing technology development more efficiently. As discussed in Section 6, these cycle costs must decline sufficiently under evolutionary acquisition to achieve net cost savings. Thus, depending on the type of system being acquired, evolutionary acquisition may actually be more expensive than traditional means of acquiring military systems. This is a critical issue for future research. However, this should not be interpreted as an endorsement of traditional acquisition methods. Instead, acquisition cycle-time can be used to control the costs of an evolutionary policy without reverting to a traditional approach that employs immature technology. A requirement for mature technologies can be consistently imposed with the next acquisition cycle beginning only when it is affordable.

There are some important caveats on this conclusion, however. First, the above results are more significant for military-specific technologies than commercial technologies. Commercial technologies will continue to develop and improve regardless of the actions of the

DoD because the DoD is actually a small player in the market. One example is microprocessor technology. On the Comanche helicopter program, the mission processing technology was changed three times because Intel introduced newer processor models faster than the DoD could develop an advanced combat helicopter (Rogers & Birmingham, 2004). For military-specific technologies, however, forward progress is dependent upon actually testing and fielding a technology and gathering user feedback. Thus, the faster acquisition cycles are, the faster learning can be incorporated into new technologies under development. Of course, faster acquisition cycles also mean that exogenously developed commercial technologies can also be moved into the field faster.

Second, evolutionary acquisition policies do not function well when the R&D process is underfunded. Evolutionary acquisition depends on a steady stream of mature technologies. When the research pipeline is "starved," not only does the performance of deployed systems decline on average, but it also becomes more unpredictable. More traditional acquisition methods mitigate this risk by using an acquisition effort to secure funding for technology development.

Third, the underfunding of middle-stage technologies, as is typical for government technology development (Cornford & Sarsfield, 2004), also adversely impacts evolutionary acquisition policies. Under these circumstances, traditional approaches to acquisition are actually superior to evolutionary methods since they mitigate the risk of technologies failing to cross the chasm. Thus, it would seem that business as usual is quite reasonable under the current funding environment for military R&D activities. Though, it is important to point out that traditional acquisition policies under this scenario still underperform evolutionary policies when R&D is fully funded.

Finally, there are several features of the current defense acquisition system that were not considered in this analysis. First and foremost among these is concurrency. For major acquisition efforts there is often substantial overlap between the technology development, system development, and production phases. While this is often an attempt to compress an otherwise long acquisition cycle, the resulting rework often increases costs and leads to performance shortfalls. This problem has been extensively documented elsewhere, and there is no need for it to be recapitulated here. If, however, the imposition of evolutionary acquisition and its shorter acquisition cycles reduced the temptation to use a concurrent acquisition strategy, it is possible that there could be a net cost savings through the reduction of rework, but that determination must be relegated to future work. Other features of defense acquisition not considered in this model are operations and maintenance costs, basic research funding, non-centralized acquisition management, program cancellation, program budgeting, the capacity of the industrial base, the capacity of the government to consume, and system integration issues. Each of these factors certainly influences the behavior and cost effectiveness of the defense acquisition system and may be examined in future work.

What we can ultimately derive from this study is that, at least to a first order, there are definite benefits to the better management and development of new technologies implied in evolutionary acquisition. A well-managed technology portfolio leads to the development of technology options, which creates the flexibility to maximize the ability of acquired systems to meet emerging threats. Traditional programs, through their early commitment to particular approaches and technologies, sacrifice some of this flexibility. The outstanding question raised is whether the increased flexibility created by evolutionary acquisition comes at additional cost. What this study revealed is that net cost savings are not automatic. Additional research is required to determine under what circumstances they are possible.

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