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Addressing Cost Increases in Evolutionary Acquisition

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Abstract

Acquisition programs are under pressure to deliver increasingly complex capability to the field without the cost growth associated with recent programs. Evolutionary acquisition was adopted to help reduce system cost (through the use of mature technologies) and to improve system performance (through faster deployment of incremental capability). While the ultimate verdict is not yet in on this decision, our previous simulation-based results have demonstrated that evolutionary acquisition can deliver improved capability more quickly than traditional acquisition, but that cost may actually increase over that of traditional acquisition. This is due to the overhead resulting from more frequent system deployment and update cycles. Are there other factors that can help reduce the cost of evolutionary acquisition? This paper investigates the role of system modularity and production level in the cost of evolutionary acquisition. Modularity typically imposes upfront costs in design and development, but may result in downstream savings in production and sustainment (including deployment of evolutionary new capability). A simulation experiment is conducted to determine under which conditions cost increases are minimized.

Introduction

In today's fiscally constrained environment, cost is a major issue that must be addressed in military acquisition. In particular, cost growth is of concern, where cost growth is the amount by which actual and projected costs increase over time from earlier cost estimates. A recent report from the Government Accountability Office (GAO) noted that for the fiscal year 2008 portfolio of weapons systems, there has been cost growth of $296 billion (GAO, 2009). Cost growth can result in fewer systems being produced than envisioned or desired (e.g., the F-22), or in program cancellation (e.g., the Navy Area Missile Defense). In the current and projected fiscal environment, there is considerable pressure to reduce costs and to rein in cost growth.

One driver of cost is the uncertainty and risk associated with development of new technologies for systems. In an effort to reduce this risk, and hence attempt to reduce costs and cost growth, evolutionary acquisition was adopted, whereby systems are developed using more mature technologies and deployed in increments of capability. At the same time, sustainment cost is increasingly factored into the overall acquisition cost equation, especially as system lifetimes increase. For instance, the contract for the F-35 Joint Strike Fighter calls for a combined production and sustainment supply network to promote cost efficiencies over the system lifecycle.

Not enough evidence has been collected to establish the effectiveness of evolutionary acquisition and preliminary efforts to address sustainment costs. Hence, our work uses computer simulation to assess the potential effectiveness of different strategies to address cost. Previous work indicates that evolutionary acquisition alone may not be sufficient to control costs (Pennock & Rouse, 2008). This paper investigates the effectiveness of evolutionary acquisition when system modularity and production level are considered. Modularity is hypothesized to help reduce sustainment costs associated with maintenance, repair and technology upgrades.

The remainder of the paper is organized as follows. Section 2 discusses acquisition costs, cost growth and the potential role of system modularity in helping address both. The simulation model used to study these issues is described in Section 3. Section 4 presents an experiment conducted to test the effect of modularity and production level on cost. Section 5 provides analysis of the overall experimental results. Section 6 focuses on those results relevant to evolutionary acquisition. Finally, Section 7 concludes and presents future research directions.

Acquisition Cost and Cost Growth

High cost and cost overruns have long been an issue with military systems. Cost growth occurs for a variety of reasons, including uncertainty and lack of knowledge about technology, design, and manufacturing (GAO, 2009). Candreva (2009) points to the role of institutional factors in organizational failures such as cost growth. One effort to address more cost effective acquisition was the introduction of evolutionary acquisition. Under evolutionary acquisition, the focus is on using technologies for new systems that are relatively mature, as opposed to traditional acquisition, which emphasizes use of new and immature technologies. The theory is that use of mature technologies tends to reduce cycle times for new system development, due to less risk in the technology development phase of acquisition (Johnson & Johnson, 2002). This should translate into reduced cost growth.

Our previous research has studied cost by focusing on the process aspects of acquisition. For instance, we have demonstrated that evolutionary acquisition processes can yield quicker deployment of capability than traditional acquisition processes, but at potentially higher cost due to overhead from the increased frequency of development cycles (Pennock & Rouse, 2008). This work did not address sustainment, however. Sustainment is estimated to constitute approximately 60% of lifecycle cost (Andrews, 2003). As a result, the acquisition community is putting more focus on sustainment, its associated costs and its potential for cost growth.

One avenue that may help address high cost in sustainment is the concept of system modularity. Modularity is an important concept in design of systems and products (Baldwin & Clark, 2000; Ulrich & Tung, 1991). Modular design seeks to reduce the dependencies between various system components. This has the potential to help improve the maintainability of a system over time and to reduce the cost of sustainment by facilitating repair and upgrade activities. Little research has quantitatively studied reduction in sustainment due to modularity, though. A number of hypotheses have been formulated in the research literature that are of interest in terms of the impact of modularity on cost.

1. Increasing modularity decreases the cost of implementing technology upgrades for deployed systems (Fleming & Sorenson, 2001; Garud & Kumaraswamy, 1995; Gershenson, Prasad & Zhang, 2003; Huang & Kusiak, 1998; Ulrich, 1995; Ulrich & Tung, 1991).

1. Increasing modularity decreases the mean time to repair a system that has failed and, hence, potentially the cost (Cheung & Hausman, 1995; Gershenson et al., 2003; Tsai, Wang & Lo, 2003).
2. Increasing modularity increases the upfront engineering design hours required for a system and hence potentially the cost (Ulrich, 1995).

These hypotheses suggest that there is a trade-off between cost savings in sustainment due to system modularity and the cost of designing a modular system. One goal of this paper is to explore this issue. Previous work has demonstrated that increased system modularity tends to facilitate reduced sustainment costs, in terms of repair and technology upgrade activities (Bodner, Smith & Rouse, 2009). The relationship is strongest for high levels of modularity, with diminishing returns as modularity levels are reduced. Thus, one question is what levels of modularity are required to balance the upstream costs of modularity design with the downstream savings from modularity.

Model Description

The simulation model used for this research can be characterized as three interacting sets of processes. First, there are the systems being developed for deployment. These are housed within programs that conduct the various activities required for acquisition. Second, there is the acquisition enterprise, which consists of a set of processes through which programs develop systems. We address both procurement and sustainment. Finally, there are exogenous effects that impact systems and acquisition.

We use discrete-event simulation, which has been used extensively for analysis of process-oriented domains such as acquisition (Law & Kelton, 2000). Our model is implemented using ARENA 12.0, a commercially available and widely used discrete-event simulation package (Kelton, Sadowski & Sturrock, 2004).

System Model

The acquisition enterprise develops a number of different systems for military use. In our model, a system is characterized primarily by its technologies in development and by its architecture in sustainment. In development, each system has several technologies that must be matured and integrated into the system so that the system can be successfully deployed. Each technology has an application area, a maturity level and a capability level. The application area describes the function of the technology (e.g., radar or stealth). The maturity level dictates its stage of progress from new and potentially promising to proven and mature. It is measured using the technological readiness level (TRL) scale (Kim, 2005) recently adopted by the DoD (DoD, 2006). The capability level characterizes the functional capability of the technology relative to others in the same application area.

In sustainment, the system architecture relates how different system components are arranged within the whole system. This architecture provides the basis for systems to have a specified modularity. In modeling system modularity, we assume that a system consists of *n* components, one of which is the system infrastructure. The infrastructure serves as the platform that integrates other components, and it is assumed to be a large-scale and static in nature over the life of the system (e.g., an airframe). Modularity is then conceptualized as a matrix denoting the relationships between components. A relationship exists when two components are connected with each other, or more specifically when changes to one component necessitate changes to another. In complex systems, components may be organized into modules, which then combine to form a system. Relationships can then exist between components within a module, between modules, or between components spanning two different modules. A relationship between two components affects whether a repair to a particular component requires a repair to another, and whether a technology upgrade to a particular component requires an upgrade to another.

For a system k, composed of n_k components, we define its repair modularity using an $n_k \times n_k$ matrix $\mathbf{R}_k$. Each entry r_{ijk} in this matrix represents the degree to which component i is related to component j for purposes of repair. This is expressed as the Bernoulli probability that a repair to component i results in a repair to component j. Similarly, we define $\mathbf{U}_k$ as the modularity matrix associated with technology upgrades, with u_{ijk} representing the Bernoulli probability that an upgrade to component i requires a compatibility upgrade to component j. Note that neither $\mathbf{R}_k$ nor $\mathbf{U}_k$ is assumed to be symmetrical. Figure 1 illustrates the concept of a repair modularity matrix $\mathbf{R}_k$ with $n_k = 6$. In the matrix, diagonal elements are defined to equal 1.0. In addition, component 1 is defined to be the infrastructure, and we assume that $r_{1jk} = 1.0$ for all $j \neq 1$, and that $r_{i1k} = 0.0$ for all $i \neq 1$. In other words, all components are assumed to be affected by a change in infrastructure, while infrastructure is assumed not to be affected by a change in any component.

1.0	1.0	1.0	1.0	1.0	1.0
0.0	1.0	0.3	0.0	0.0	0.0
0.0	1.0	1.0	0.0	0.3	0.5
0.0	0.5	1.0	1.0	0.0	0.0
0.0	0.0	0.0	0.0	1.0	0.0
0.0	0.0	0.0	0.0	0.0	1.0

Figure 1. System Modularity

We use the concept of a modularity index to parameterize the extent to which a system is modular (Guo & Gershenson, 2004; Hölttä-Otto & de Weck, 2007). Since modularity is matrix-based and, hence, multidimensional in nature, an index provides a more concise characterization of modularity. Our particular index for a repair modularity matrix is defined below:

$$m_{rk} = \frac{1}{(k-1)(k-2)} \sum_{i=2}^{n_k} \sum_{j=2, j \neq i}^{n_k} r_{ijk}$$

This index is the average of the probabilities that two different non-infrastructure components are related for repair purposes. A system whose index m_{rk} is small, is considered more modular that one whose index is large. The modularity index m_{uk} for technology upgrades is defined similarly.

A system typically has a projected production level, targeted to provide the number of units needed to meet the need for which the system is being developed. This projected production level can change over time, as threats change, as new technologies/systems become available, or as costs escalate. Let P_k = the actual production level for system k.

Acquisition Enterprise Model—Procurement

The acquisition enterprise consists of the five phases of a defense acquisition program, as defined by the DoD *Defense Acquisition Guidebook* (DoD, 2006). These phases include concept development, technology development, system development, production & deployment, and operations & support. Here, the focus is on the procurement phases of acquisition, i.e., the first four phases. Operations and support is analogous to sustainment and is discussed in the next section. These phases are illustrated in Figure 2.

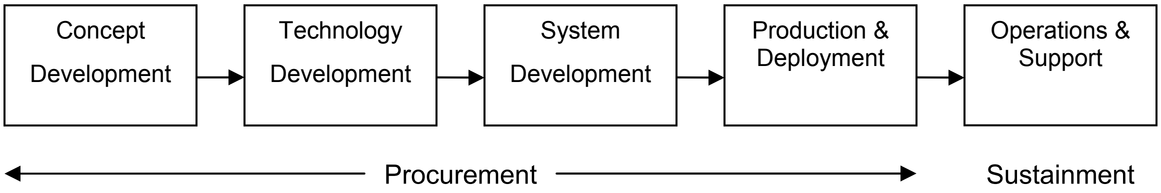

Figure 2. Phases of Acquisition

A program starts in the first phase and proceeds through the remaining phases. Sometimes, this process involves concurrency, or overlap between parts of two different phases (e.g., overlap between final testing in system development and low rate initial production). In the procurement phases (the first four phases of acquisition), each phase is characterized by duration and a cost for the program. Once a phase is concluded, the program moves onto the next phase. The model assumes no concurrency. This basic model, which does not incorporate modularity or production level, is described in greater detail by Pennock and Rouse (2008), who also discuss the parameters used for cost and duration figures for the various procurement phases. Elaborations in system development and in production are discussed below.

- <u>Concept development</u>. Concept development is assumed to last for a duration of between 2 and 7.5 years, with a mode of 4.9. Cost is assumed to be a linear function of duration, with rate $20 million/year.
- <u>Technology development</u>. The cost and duration of the technology development phase depends on whether the program is using evolutionary or traditional acquisition, as the program must mature the technologies to be used for the system if it uses traditional acquisition. Technologies for systems being acquired are developed exogenously to the acquisition enterprise, from the military science and technology (S&T) enterprise. These technologies are then brought into a program when needed in the technology development phase. The maturity level of the technologies brought into a program is used to characterize traditional acquisition versus evolutionary acquisition. The development process is risky, in that individual technologies may fail, thus causing a longer technology development phase (and higher cost) for the program. A program that uses immature technologies typically has a longer, costlier and riskier technology development phase than one that uses relatively more mature technologies. The duration and cost of this phase is the time and cost needed to develop the needed technologies for the system.
- <u>System development</u>. Here, we assume that the development cost and time are dependent on the level of modularity. In particular, they are increasing functions

of modularity. We assume a linear relationship between cost and time. For simplicity, repair and upgrade modularity are assumed to be the same in the model, with a modularity index denoted simply as $m_{rk} = m_{uk} = m_k$. Recall that as m_k increases, the system is characterized by a lesser degree of modularity. We then let the system development time T_{dk} be defined

$$T_{dk} = Ae^{-am_k}$$

Here, A is a scale factor related to the time in years, and a is a scale factor that represents the increasing effort it takes to make a system marginally more modular. In the model, system development time is scaled to lie between 1.5 and 8 years, and its cost is a linear function of duration at a rate of $1,000 million.

- Production & deployment. The cost and duration of the production phase are, obviously, dependent on the production level of the system in question. We use the Cobb-Douglas production function, a standard micro-economic model that relates input units to units produced to allow for increasing, constant or decreasing returns to scale (Kreps, 1990). Letting X_k = input resources used for system k, P_k = production of k, and b = scale factor, the functional form is

$$P_k = X_k^b$$

Inputs here are capital, labor and materials. Letting $b > 0$ yields increasing returns to scale, which is typical for production of complex systems. Assuming a constant cost for inputs B_k, and letting Z_k = the cost of the production phase, we obtain

$$\begin{aligned} Z_k &= B_k X_k \\ &= B_k P_k^{1/b} \end{aligned}$$

To determine the mean time needed for the production phase for a given production level, Z_k is scaled to a cost between $6,000 million and $18,800 million, and the production time is determined using a linear relationship between cost and duration with a rate of $4,000 million/year.

Acquisition Enterprise Model—Sustainment

The sustainment model includes repairs and technology upgrades for a particular system k. The production level P_k is assumed to be the fleet size for the duration of sustainment (i.e., no systems are lost or retired). Failures and technology upgrades are assumed to occur randomly according to a Poisson process. Each failure or technology upgrade affects only one component directly. Due to modularity, though, a repair to component i may require a repair to another component j (with probability r_{ijk}). Similarly, an upgrade to i may require an upgrade to another component j (with probability u_{ijk}). The rates for the failure and technology upgrade processes are defined below.

- f_i is the failure rate associated with component i.
- g_i is the repair rate associated with component i.
- t_i is the arrival rate of new technology upgrades for component i.
- v_i is the upgrade rate for component i.

- p_i is the cost of repairing component i.
- q_i is the cost associated with a technology upgrade to component i.
- c_{ij} is the compatibility cost associated with making component j technologically compatible with component i if i is upgraded, and if the interaction between i and j necessitates that j be made compatible to the new technology for i.

Since infrastructure is not affected by repairs or technology upgrades, we assume that f_1, g_1, t_1, v_1, p_1, q_1, c_{i1} and c_{1j} are not defined. In general, it is assumed that $f_i > t_i$, $g_i > v_i$, and $p_i < q_i$.

Once a system is deployed into sustainment, it experiences failures and technology upgrades for its various components according to the above rates. Technology upgrades are a significant concern for systems with long sustainment lifecycles (Singh & Sandborn, 2006). A failure invokes a repair process, and a technology upgrade opportunity invokes an upgrade process. Upon occurrence of a failure in component i, all other components j ($\neq 1$) with $r_{ijk} > 0$ are evaluated probabilistically, using random number generation, to determine if a repair is necessary for j. Any additional components are then repaired. The cost is the summation of the repair to the original component i and the cost of other components being repaired. Upon occurrence of a technology upgrade for component i, all other components j ($\neq 1$) with $u_{ijk} > 0$ are evaluated probabilistically, using random number generation, to determine if a compatibility upgrade is necessary for j. Any additional components are then made compatible. The cost is the summation of the summation to the original component i and the cost of other components being made compatible. If a failure or technology upgrade for i arrives while the system is in downtime, that failure or technology upgrade queues until the downtime is resolved. Multiple entities in this queue are processed first-come-first-served. This process continues for the sustainment life of the system over the active fleet, which is assume to range between 15 and 40 years, with a mode of 20 years at a median rate of $965 million per year. The actual rate is influenced by the production level.

This model provides cost for the direct activities involving maintenance and repair (including upgrades) within the sustainment phases. Clearly, sustainment encompasses many other costs. Unger (2009) presents analysis of the sustainment cost categories from the DoD's Cost Analysis Improvement Group (CAIG) for Air Force programs. Approximately 52.5% of sustainment cost can be categorized as related to maintenance and repair. We assume that approximately half of these costs (i.e., 25% of sustainment costs) are tied to direct repair and upgrade activities represented in our sustainment model.

It should be noted that there is no effect on the sustainment phase from the acquisition policy used in the procurement phases (i.e., traditional versus evolutionary).

Exogenous Model

Exogenous to the acquisition enterprise are two important outside influences. The first is a model of technical progress, which represents basic research performed in the commercial world or via non-defense government funding. Results from this model are immature technologies that are input into the second exogenous influence, the DoD science and technology (S&T) enterprise. These new technologies enter the S&T enterprise at TRL 1. Technologies generated by the model of technological progress increase in capability as time progresses using a capability growth function that combines a learning effect (from other DoD applications) and an exogenous progress effect (from commercial and outside technical progress).

The technology development process model matures new technologies for DoD systems, typically using a staged process of development whereby ideas are reduced to working technologies that can be integrated into a system. There is considerable technical risk in the development process, as ideas often do not work in practice, do not scale up to production, or do not integrate into systems. The staged process mitigates risk by not fully funding a technology's development, allowing it to be culled if it fails or if it is outpaced by competing technologies. It should be noted that the S&T enterprise model consists of a single, unified organization, rather than the myriad agencies that comprise the actual DoD S&T enterprise.

Experiment

This section describes the experiment to be conducted.

Parameters

We use the following parameter values in the simulation model for the experiment:

- $a = 1.3$
- $b = 1.25$
- $1/t_i \sim$ Triangular (5, 8, 15) years for all i and over all systems
- $1/f_i \sim$ Triangular (1.5, 2.5, 4) years for all i and over all systems
- $p_i \sim$ uniform (0.025, 0.075) $ million for all i and over all systems
- $q_i \sim$ uniform (0.2, 0.2375) $ million for all i and over all systems
- c_{ij} = $0.1 million for all i and j and over all systems
- k = 6 over all systems

It should be noted that t_i and f_i are parameters for Poisson processes, and that their inverses are the inter-arrival times for those respective processes, distributed as exponential variables. Thus, their inter-arrival times are shown here. Repair times and upgrade times are assumed to be instantaneous.

Experimental Design

The goal is to study the effect of system modularity and production level on acquisition cost, including sustainment, with a particular focus on cost of evolutionary acquisition. Thus, we adopt a factorial experimental design with three independent variables, as outlined in Table 1.

Table 1. Experimental Design

Independent Variable	Level 1	Level 2
Acquisition Policy	Traditional	Evolutionary
Modularity Index	0.50 (Low)	0.25 (High)
Production Level	250 (Low)	500 (High)

This results in a 2^3 factorial experiment. We are interested in studying the following six dependent variables:

- C_1 = program procurement cost
- C_2 = program sustainment cost
- C_3 = total program cost = $C_1 + C_2$
- C_4 = annualized procurement cost over all systems
- C_5 = annualized sustainment cost over all systems
- C_6 = annualized cost over all systems = $C_4 + C_5$

Each simulation replication is run for a period of 150 years, with a warm-up period of 50 years preceding. This allows analysis of the steady-state enterprise behavior, since the enterprise model needs a warm-up period to reach steady-state. After the warm-up period, the statistics collection begins. Ten replications of each combination of factors are conducted to allow for statistical significance.

Experimental Results

Table 2 provides summary experimental results. Columns two through four contain the level of each independent variable as shown in Table 1. The value shown for each dependent variable in columns five through ten is the average over the ten replications. The units of the dependent variables are in millions $.

Table 1. Summary Experimental Results

Run	Policy	Mod.	Prod.	C_1	C_2	C_3	C_4	C_5	C_6
1	1	1	1	12,657	22,248	34,906	5,305	5,075	10,380
2	1	1	2	18,640	26,409	45,049	6,378	5,653	12,031
3	1	2	1	13,832	20,623	34,455	5,378	4,441	9,819
4	1	2	2	20,078	23,096	43,174	6,189	4,296	10,485
5	2	1	1	11,518	22,248	33,766	5,960	6,316	12,276
6	2	1	2	17,548	26,409	43,957	7,071	6,556	13,627
7	2	2	1	12,629	20,623	33,252	5,884	5,210	11,094
8	2	2	2	18,910	23,200	42,109	6,981	5,290	12,271

Analysis of Overall Results

We use a balanced analysis of variance (ANOVA) method to determine which independent variables (or factors) have significant effects (Box, Hunter & Hunter, 1978). The ANOVA also computes whether there are significant interaction effects among more than one factor. In performing the analysis of variance for this experiment, Minitab® version 15 software is used. Tables 3 through 8 report the analysis of variance for each of the dependent variables, C_1 through C_6, respectively. Main effects from each independent variable are noted, as are interaction effects among independent variables.

Table 2. Analysis of Variance for Program Procurement Cost (C_1)

Source	**DF**	**SS**	**MS**	***F***	***p***
Policy	1	26486575	26486575	384.31	0
Mod	1	32315116	32315116	468.88	0
Prod	1	752794480	7.53E+08	10922.85	0
Policy*Mod	1	24451	24451	0.35	0.553
Policy*Prod	1	8505	8505	0.12	0.726
Mod*Prod	1	330508	330508	4.8	0.032
Policy*Mod*Prod	1	207	207	0	0.956
Error	72	4962185	68919		
Total	79	816922028			

From the analysis, we infer that each of the main effects are significant (with $p < 0.10$), as is the interaction effect between modularity and production level. Similar to Pennock and Rouse (2008), programs using evolutionary acquisition tend to have a lower program cost than those using traditional acquisition, due to higher technology development costs. As expected, low levels of modularity have lower procurement costs, due to less systems engineering work in the development phase. Also as expected, higher production levels lead to higher procurement costs. High modularity and high production level interact to increase procurement cost more than each individual factor.

Table 3. Analysis of Variance for Program Sustainment Cost (C_2)

Source	**DF**	**SS**	**MS**	***F***	***p***
Policy	1	13394	13394	0.01	0.933
Mod	1	119354720	119354720	63.02	0
Prod	1	223440510	223440510	117.97	0
Policy*Mod	1	13394	13394	0.01	0.933
Policy*Prod	1	13394	13394	0.01	0.933
Mod*Prod	1	13382709	13382709	7.07	0.01
Policy*Mod*Prod	1	13394	13394	0.01	0.933
Error	72	136366569	1893980		
Total	79	492598085			

For sustainment cost, there is no effect from acquisition policy. This is to be expected, since the simulation model assumes no difference in the sustainment profile between the two policies. However, the effects from modularity, production level and their interaction are significant. Low levels of modularity tend to cause higher sustainment costs, and high production levels, of course, result in higher sustainment costs. Introducing high modularity into a system tends to mitigate the sustainment cost increase associated with high production levels.

Table 4. Analysis of Variance for Total Program Cost (C_3)

Source	DF	SS	MS	*F*	*p*
Policy	1	25308713	25308713	12.6	0.001
Mod	1	27460953	27460953	13.67	0
Prod	1	1796490516	1796490516	894.42	0
Policy*Mod	1	1651	1651	0	0.977
Policy*Prod	1	43247	43247	0.02	0.884
Mod*Prod	1	9506987	9506987	4.73	0.033
Policy*Mod*Prod	1	10271	10271	0.01	0.943
Error	72	144615531	2008549		
Total	79	2003437868			

Looking at total program cost, each of the main effects is significant, as is the interaction between modularity and production level. The effect of the main factors is explained by the combined effect of these factors on the constituents of C_3 (i.e., C_1 and C_2). However, the effect of modularity combines opposite effects noted in C_1 and C_2. The effect of reduced cost from increased modularity noted in sustainment cost wins out, as sustainment costs overpower development costs. Similarly, the interaction effects between modularity and production level in each of the constituents are in opposite directions. Once again, the effect from sustainment costs wins out, and we can infer that high modularity helps mitigate the effect of cost increases due to high production levels.

Table 5. Analysis of Variance for Annualized Procurement Cost (C_4)

Source	DF	SS	MS	*F*	*p*
Policy	1	8745812	8745812	853.98	0
Mod	1	99301	99301	9.7	0.003
Prod	1	20921804	20921804	2042.9	0
Policy*Mod	1	3027	3027	0.3	0.588
Policy*Prod	1	131703	131703	12.86	0.001
Mod*Prod	1	94557	94557	9.23	0.003
Policy*Mod*Prod	1	78033	78033	7.62	0.007
Error	72	737368	10241		
Total	79	30811604			

In analyzing annualized procurement cost, we find that each of the main effects is significant, as are most of the interaction effects. Confirming Pennock and Rouse (2008), the annualized procurement cost for evolutionary acquisition is significantly higher than that of traditional acquisition. This is due to the higher number of refresh procurement cycles. Similar to C_1, high production levels are associated with higher annualized costs. However, in this case, low levels of modularity are associated with higher annualized costs, in contrast to the effect from C_1. This is likely due to the increased development time required for high levels of modularity, which reduces the number of systems deployed over the lifecycle and, hence, the annualized cost. Likewise, there is a corresponding significant interaction effect between modularity and production levels whereby low levels of modularity in conjunction with high production levels are associated with increased costs. Interestingly, there is a significant interaction effect here between acquisition policy and production level. The increased number of programs under evolutionary acquisition interacts with high production levels to increase annualized procurement costs more than each individual factor. Finally, there is a three-way interaction effect among all independent variables. This is manifested as a reduction in the difference in cost between different production levels and acquisition policies as modularity level is increased.

Table 6. Analysis of Variance for Annualized Sustainment Cost (C_5)

Source	DF	SS	MS	*F*	*p*
Policy	1	19079848	19079848	134.12	0
Mod	1	23789768	23789768	167.23	0
Prod	1	707084	707084	4.97	0.029
Policy*Mod	1	181790	181790	1.28	0.262
Policy*Prod	1	16048	16048	0.11	0.738
Mod*Prod	1	971557	971557	6.83	0.011
Policy*Mod*Prod	1	397276	397276	2.79	0.099
Error	72	10242758	142261		
Total	79	55386129			

For annualized sustainment cost, the three main effects are again significant. For modularity and production level, these effects are consistent with the reasons noted for program sustainment cost C_2. For acquisition policy, the effect is consistent with the analysis for annualized procurement cost C_4, i.e., the increased number of refresh cycles means that there is an increased number of programs needing sustainment. In this model, we assume that the program sustainment profiles are the same under evolutionary and traditional acquisition. This does not account for the possibility that, under an evolutionary system, it may be the case that system lifecycles are reduced, allowing a reduction in sustainment costs. The interaction effect between modularity and production level is consistent with the effect noted for individual program sustainment cost C_2, whereby high modularity mitigates cost increases associated with high levels of production.

Table 7. Analysis of Variance for Annualized Total Cost (C_6)

Source	DF	SS	MS	*F*	*p*
Policy	1	53661197	53661197	292.72	0
Mod	1	26963050	26963050	147.08	0
Prod	1	29321345	29321345	159.95	0
Policy*Mod	1	231729	231729	1.26	0.265
Policy*Prod	1	55804	55804	0.3	0.583
Mod*Prod	1	1672308	1672308	9.12	0.003
Policy*Mod*Prod	1	827448	827448	4.51	0.037
Error	72	13199104	183321		
Total	79	125931985			

Finally, in terms of annualized total cost, each of the three main effects is significant, as is the interaction effect between modularity and production level. The effect for acquisition policy is explained by the effect noted for the constituents of C_6 (i.e., C_4 and C_5), i.e., the increased number of programs due to evolutionary acquisition. The effect for modularity is explained by the larger effect of modularity in reducing sustainment costs than increasing procurement costs, while the effect of production level is explained simply by the increased cost of producing and sustaining more units.

Analysis of Evolutionary Acquisition

We now focus on evolutionary acquisition by analyzing the experimental results that just pertain to it. The observations below summarize our findings relative to those of the overall experiment. These results come from reducing the observations to a 2^2 factorial experiment involving only modularity and production level as independent variables.

- For C_1, the program procurement cost, both modularity and production level have similar significant effects. The interaction effect is somewhat weaker, though, registering only a *p*-value of 0.136. Thus, we infer that this interaction effect predominates for traditional acquisition due to the relatively larger program procurement cost.
- Similarly, for C_2, the annualized sustainment cost, both modularity and production level have the same type of significant effect. The interaction effect is also somewhat weaker than in the overall experiment, with a *p*-value of 0.077.
- The same observations hold for C_3. Here, for the effect of modularity and the interaction effect between modularity and production level, the sustainment cost predominates, causing increased modularity to have a reducing effect on the total program cost. The *p*-value for the interaction effect is relatively weak at 0.138.
- For the annualized costs (C_4, C_5 and C_6), modularity retains its significant effect in the same direction as in the overall experiment. However, production level is significant only for C_4 and C_6. In addition, the interaction effect between modularity and production is not significant across the three dependent variables. This is likely captured in the three-way interaction effect among the three independent variables noted in the overall experiment for C_4, C_5 and C_6. It may be that additional replications are needed to get statistically significant results for these effects. This bears further investigation.

Discussion and Future Research

The above results imply a number of conclusions relevant for military acquisition.

- Increased system modularity yields increases in the system development cost, but the decrease in sustainment cost over the system lifecycle may more than compensate for these increased costs. This points to the need to view acquisition as an investment process. While the short-term budgeting nature of the federal government works against this perspective, a longer term view does show the benefit of investing current costs to achieve long-term savings.
- Modularity can help mitigate the cost increases associated with higher production levels through an interaction effect between these two factors. Similar to the previous point, this effect involves the way in which sustainment costs overpower those of development, due to long lifecycles.
- Evolutionary acquisition seems less susceptible, especially from an annualized cost point of view, to this interaction effect between modularity and production levels. While this bears further investigation, it should be noted that those

programs that do maintain characteristics of traditional acquisition may wish to investigate this phenomenon.

- Evolutionary acquisition may decrease individual program costs, but the more frequent refresh cycles may drive cost growth in overall procurement and sustainment. Thus, discretion is needed in managing these refresh cycles, especially when high production levels are involved.

This work has addressed the process aspects of the acquisition enterprise. Clearly, processes are an important and critical part of the acquisition enterprise. However, acquisition occurs in the context of organizational behavior that is impacted by incentives and information availability. The DoD has spent significant resources on incentive programs to facilitate positive acquisition outcomes. Some research suggests that these resources have not been used effectively (GAO, 2005). However, economic research suggests that it is possible to design incentive programs under different information availability scenarios (Hildebrandt, 2009). Thus, an avenue of future research is to integrate organizational behavior modeling of acquisition, combined with process modeling.

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