A Model for EXOGENOUS LEARNING on DEPARTMENT OF DEFENSE Procurement Programs

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Evidence of exogenous learning on Department of Defense (DoD) procurement programs for major weapon systems acquisition can be demonstrated and explained with an investment strategy model that maximizes the manufacturer's return on investment (ROI) over the life of the program. This article describes one such model. The model takes a list of investment and unit-cost-reduction pairs and a planned procurement profile and computes which investments should be made and in what order to maximize profit. Simulations conducted with this model explore the learning curve effects caused by regulatory lag (the period of time the contractor gets to keep the ROI before he has to pass savings onto the customer), the manufacturers' expected profit, and changes to the procurement rate.

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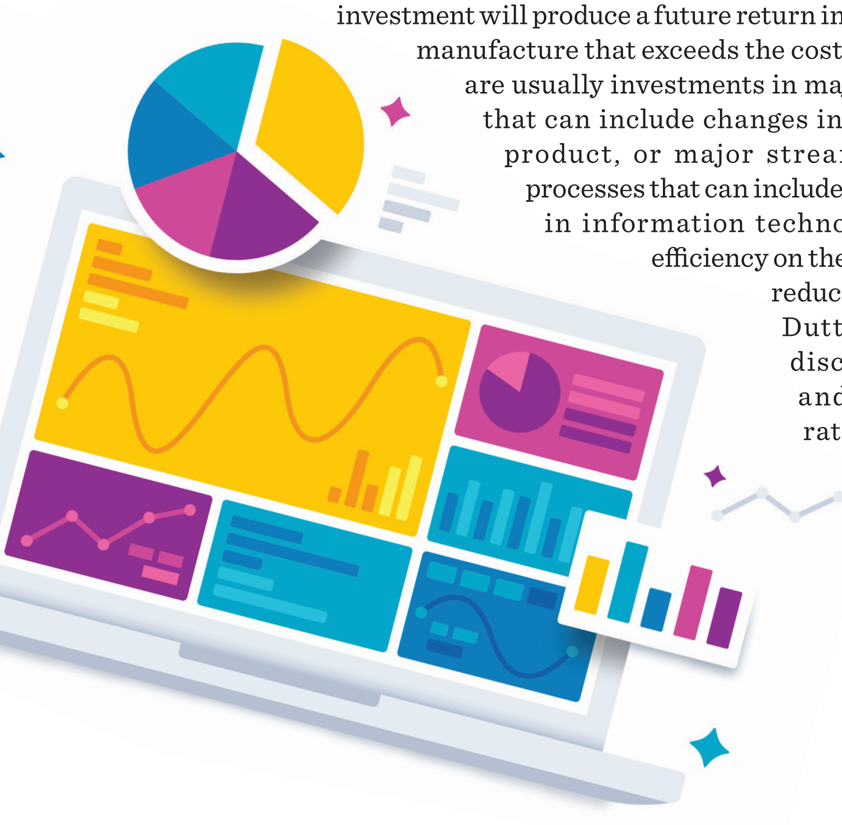
Exogenous Learning Based on Economic Incentives

A learning curve is a graphical representation of the cost of producing an item against the number of items produced over time. In 1936, Theodore Paul Wright described the effect of learning on production costs in the aircraft industry (Wright, 1936). Comprehensive reviews exist on learning curves (Womer, 1979), the theory behind them (Adler & Clark, 1991; Hall & Howell, 1985; Zollo & Winter, 2002), and empirical analysis of manufacturing data (Ittner et al., 2001). From these sources and others (Lapr'e & Nembhard, 2010), it is known that learning occurs with repetition because workers make fewer mistakes and spend less time thinking and hesitating. It is also known that learning occurs when workers and resident production engineers modify the manufacturing process with preexisting resources. For example, engineers can streamline existing processes, standardize processes across manufacturing lines, and make better use of existing equipment. Furthermore, changes made by management, such as changes in the labor mix, can also improve learning for a manufacturing process. All these reasons for increased efficiency are internally driven improvements and do not require a specific monetary investment; this type of learning is known as *endogenous learning*.

Exogenous learning, conversely, requires the company to invest money up front, to change something specific, with the expectation that the investment will produce a future return in the form of lower costs to manufacture that exceeds the cost of the investment. These are usually investments in major design improvements that can include changes in material content of the product, or major streamlining of production processes that can include automation. Investments in information technology can also increase efficiency on the manufacturing floor and reduce overhead support costs. Dutton and Thomas (1984) discuss "induced learning" and suggest the learning rate should be treated as a dependent variable. Zollo and Winter (2002) call it deliberate learning and suggest that tasks with high



economic importance should benefit from relatively higher investments. Hax and Majluf (1982) observed that investments can result in shifts to steeper learning curves.

Lee (1977) relates economic incentives inherent in DoD production programs and contracts to the shape of the learning curve and considers economic incentives to be returns on investment (ROIs) that drive the unit cost down. When price is closely coupled to cost, which is true in most DoD procurement contracts for major weapons systems, Lee concludes that manufacturers have few economic incentives to invest in producibility and production technology that lower the cost to manufacture. If the cost of the items go down over the life of the program, so does the profit.

"Exogenous learning, conversely, requires the company to invest money up front, to change something specific, with the expectation that the investment will produce a future return in the form of lower costs to manufacture that exceeds the cost of the investment.

Rogerson (1994) proposes that "regulatory lag" provides economic incentives for manufacturers to invest in cost-reduction initiatives when price is closely coupled to cost. As used by Rogerson, regulatory lag is a period of time that a manufacturer gets to keep ROIs before having to pass the savings onto DoD. At the end of that time period, the manufacturer must share its cost savings, and this is negotiated and written into the next contract. A long regulatory lag period translates into greater incentive for the manufacturer to reduce cost. Consequently, when potential investments to reduce production cost exist, regulatory lag becomes a major driver in determining the degree of learning on DoD procurement programs.

To complicate the manufacturer's decision process, DoD makes changes to the planned procurement profile with consequences to the manufacturer's expected ROI. If quantities are increased during the regulatory lag period, the returns increase, and if quantities are reduced during the regulatory lag period, the returns decrease from what was expected. This complication provides a negative incentive for the contractor to invest, especially when programs are routinely stretched to buy to the budget. On the other hand, multiyear procurement contracts create a positive incentive to invest because their use increases regulatory lag from a more normal 1 to 2 years out to 5 to 7 years.

The Decision-Making Model for Learning Based on Economic Incentives

The theoretical decision-making model described in this article is based on ideas in lecture notes of Rogerson (1994) for exogenous learning on a production program. The model takes the following inputs:

- A baseline endogenous learning curve
- A list of available investments that each yield a specific reduction in unit costs
- A planned procurement profile that specifies the yearly quantity per lot for the entire length of the procurement program
- The length of the regulatory lag period
- The manufacturer's expected profit
- The cost of capital (time value of money)

The model calculates the net return on each investment made in each year of the regulatory lag period and weighs it against the investment made to produce the reduction and the profit loss that will be experienced in future years because of the cost reduction. It can also compute the results of making an investment or not each year, just as the manufacturer could. However, it is constrained to use an investment-return pair only once, if at all. Lastly, the model computes outcomes on which investments should be made and in what order to maximize profit.

The outcome of a simulation conducted with the model represents the manufacturer's planned investment strategy for that specific procurement profile. With the planned investment strategy, the model generates the average cost per unit per lot, which is the learning curve that reflects both endogenous and exogenous learning on the program.

Starting with a list of investment-return and a planned procurement profile, the model builds a matrix that represents all realistic outcomes of the decision process.

The investment-return pair is represented in the model by I_{ij} and r_{ij} where the subscript i specifies the investment and the subscript j identifies the first period where the return will be realized, so that r_{ij} is the reduction in unit cost resulting from investment i made in lot j.

The cost of lot *j* can be written as in Equation 1 and is the exogenous learning curve:

$$C_j = q_j \times c_j - q_j \sum_{i=1}^{j} r_{ij} \ , \qquad \text{(Equation 1)}$$

where q_j is the quantity in lot *j*, and c_j is the average unit cost of lot *j* before any investments are made.

The model then populates the matrix with the information upon which the decision is based—that is, the net present value of the changes in profit. Equation 2 represents the net present value of the changes in profit due to investment ***i*** made in year ***j***:

$$P'_{ij} = \sum_{i=j+1}^{j+1+\lambda} q_l \, r'_{i\lambda} - \Upsilon \sum_{l=j+2+\lambda}^{N} q_l \, r'_{i\lambda} - I_{ij} \ , \qquad \text{(Equation 2)}$$

where $r'_{i\lambda}$ is the net present value of the reduction in cost, λ is the number of years before prices adjust to reflect lowered costs (the regulatory lag period), Υ is the manufacturer's expected profit rate, and *N* is the total number of years in the procurement program.

The first term in Equation 2 is the net present value of the cost reduction for λ years, after which the government reduces the offered price to account for the cost savings. The second term in Equation 2 represents the manufacturer's profit loss because of the reduction in cost, and the third term is the cost of the investment ***i*** in year ***j***. It is interesting to note that, because the profits from reduction in cost are limited to a fixed number of years, and the losses from reduced profit extend to the end of the program, it can be optimal for the contractor to delay or not even make an investment to lower cost.

With the investment-return pairs and subsequent changes in profit defined, the model computes the stream of investments that maximizes the net present value of profit as given by Equation 2. In this application, a binary integer-programming routine returns the optimum order of the investment and represents the manufacturer's preferred investment profile given the planned production quantities per year. The model utilizes the binary integer programming routine available in MathWorks Optimization Toolbox™, Version 7.5 (R2007b). It is appropriate to use binary integer programming when each variable in the optimal solution can be represented as either a 0 or a 1. For this application, the condition was satisfied by presenting the decision-making model (or the manufacturer) with a list of investment-and-return pairs and a planned procurement quantity profile, and let the model either make an investment (1) or not make an investment (0) in a given period.

Numerical Experiments

Numerical experiments are designed to explore the optimal learning curve's sensitivity to the length of the regulatory lag period, the manufacturer's expected profit, the cost of capital, and reductions in the planned procurement quantity per lot.

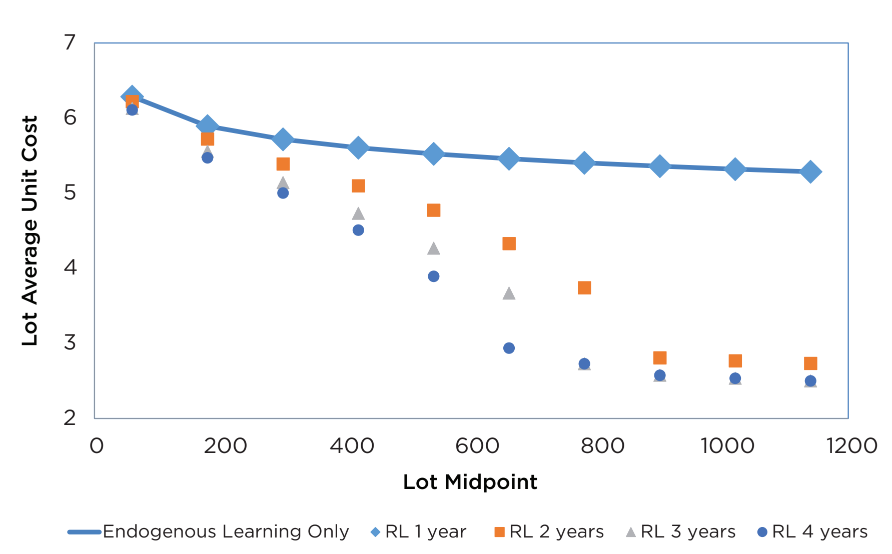
Each experiment starts with a list of 20 investment and unit-cost-reduction pairs. The unit-cost-reduction values vary from about 1% to about 11% of the first unit cost. If all 20 reductions were realized, the unit cost would be about 50% of the first unit cost. The investment and unit-cost-reduction pairs are specified so that each investment returns at least its cost over 2 years relative to a 10-year baseline program. Each cost-reduction investment is sized to matter, and the magnitude of the maximum possible reduction is plausible. These conditions are, at least nominally, realistic for the experiments performed, that is, to examine how exogenous learning changes as the variables for regulatory lag period, length of the procurement program, manufacturer's expected profit, and the time value of money are changed.

Experiment 1: Varying the Regulatory Lag Period

This experiment starts with a procurement program that buys 1,200 units over a 10-year period at a rate of 120 units per year. The endogenous learning curve slope for this contract is assumed to be 96% (the remainder of the learning to be earned by investments), the manufacturer's expected profit is 10%, and the cost of capital is 7%. Four scenarios explore the results when the regulatory lag period increases from 1 to 4 years.

Figure 1 presents the results of Experiment 1 in graphical form with average unit cost per lot versus lot midpoint for each scenario, and the endogenous learning curve shown for reference.

FIGURE 1. LEARNING CURVES ON A 10-YEAR PROGRAM WITH REGULATORY LAG 1, 2, 3, & 4 YEARS



With the regulatory lag period 1 year long, there is no exogenous learning because the model did not make any investments. With regulatory lag periods of 2 years, the model makes investments in years 1 through 8, producing a steeper learning curve (average slope of about 82% over the life of the program). With increasing length of the regulatory lag period, the model generates more and sometimes different investments with the number of investments increasing (and the slope of the learning curve) with each year added. According to this simulation, 2 years of regulatory lag reduces total procurement cost on the 10-year program by 22% from the purely endogenous case.

Experiment 2: Stretching a Procurement Program

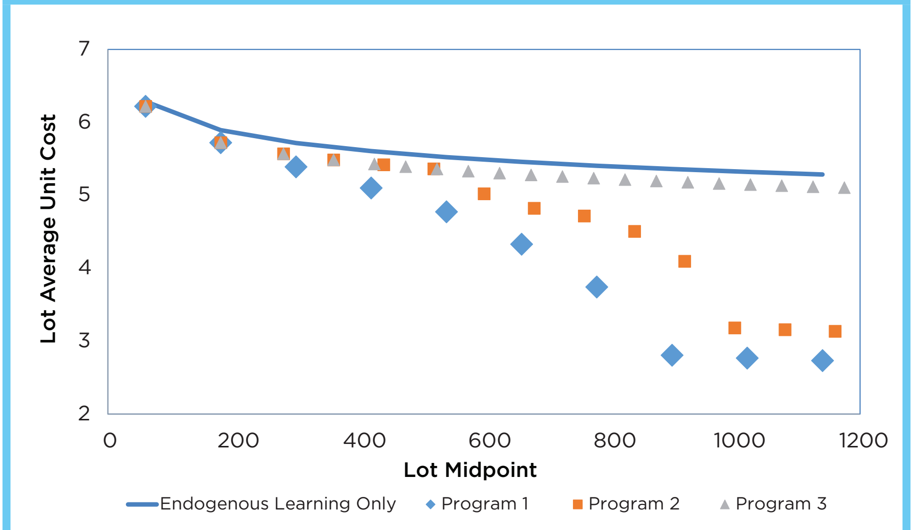
This experiment starts with a procurement program that buys 1,200 units over a 10-year period at a rate of 120 units per year (Program 1). The endogenous learning curve slope for this contract is 96%, the manufacturer's expected profit is 10%, the cost of capital is 7%, and the regulatory lag is 2 years. The initial investment plan is calculated before production begins.

Program 2 reflects the result of a decision made during the first year of production to stretch the procurement program starting in year 3. The program is stretched to 14 years by decreasing the planned procurement quantity from 120 to 80 per year, from year 3 through year 14.

Program 3 reflects the result of a decision made in year 2 to stretch the program again, starting in year 5, by decreasing the planned procurement per year from 80 to 50, resulting in a 20-year procurement program.

Figure 2 presents the results of Experiment 2 in graphical form with average unit cost per lot versus lot midpoint for each scenario, and the endogenous learning curve shown for reference.

FIGURE 2. LEARNING CURVES DEMONSTRATING LOSS OF LEARNING AS THE PROGRAM IS STRETCHED

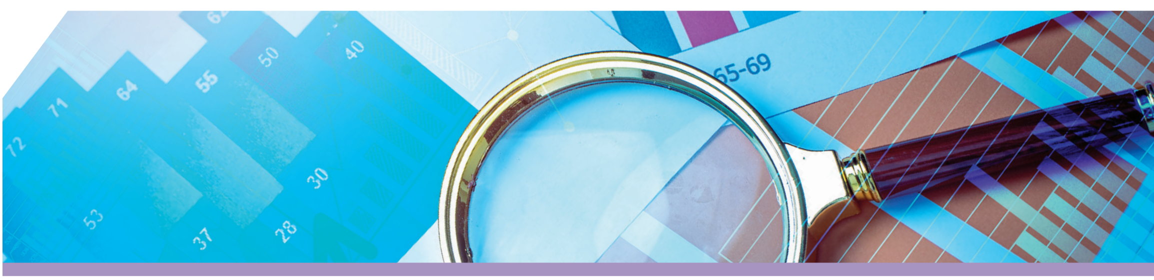


Investments are made in Program 1 that increase exogenous learning each year from years 1 through 8. When the program is stretched starting in year 3, no investments return a positive net present value until year 7. Investments are made in years 6 through 11 for reductions in years 7 through 12. When the program is stretched the second time starting in year 5 (Program 3), exogenous learning stops. The loss of learning from the first stretch increases the total procurement cost by 11% and the second stretch to 24%.

Recall, the model was designed with no fixed cost per lot, so the changes in cost could be attributed to changes in the shape of the learning curve.

Experiment 3: Varying Manufacturer's Expected Profit

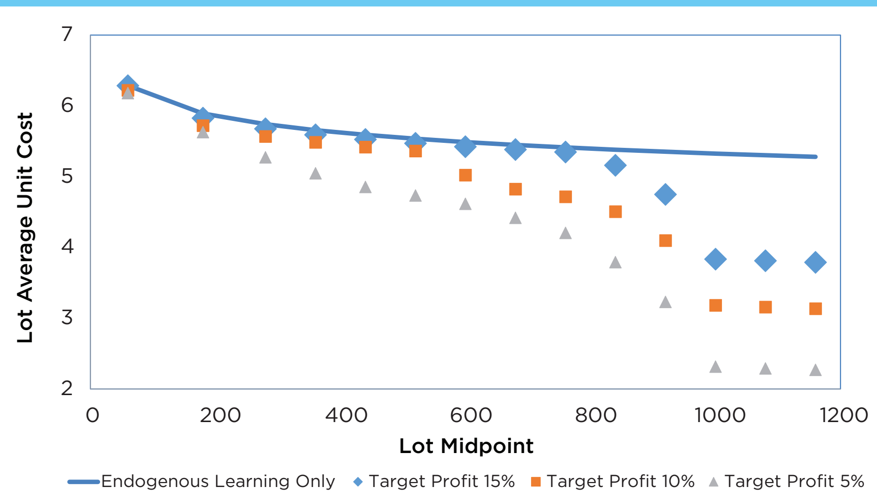
If the cost to manufacture an item is reduced after award of a firm-fixed-price (FFP) contract, the manufacturer gets to keep the difference as *additional* profit. (Note: An FFP contract provides for a price that is not subject to any adjustment on the basis of the contractor's cost experience in performing the contract. This contract type places upon the contractor maximum risk and full responsibility for all costs and resulting profit or loss. It provides maximum incentive for the contractor to control costs and perform effectively and imposes a minimum administrative burden upon the contracting parties [Federal Acquisition Regulation, 2019, § 16.2].)



Experiment 3 explores the consequences of changing the manufacturer's expected profit.

Figure 3 presents the results of Experiment 3 for Program 2 (stretched starting in year 3) in graphical form with average unit cost per lot versus lot midpoint for each scenario, and the endogenous learning curve shown for reference.

FIGURE 3. LEARNING WITH VARIOUS TARGET PROFIT VALUES



Reducing the manufacturer's expected profit reduces the cost of the procurement program. Recall that the decision to invest or not depends not only on the investment and cost reductions during the regulatory lag period but also on the profit loss due to those reductions after the end of the regulatory lag period. In this case, only three investments are made when the profit is 15%, 6 investments are made when the profit is 10% (lowering the total production cost by 7%), and 10 investments are made when the profit is 5% (lowering the total production cost by 17%).

Manufacturer's Profit and DoD Costs

This learning model features a decision process that represents the manufacturer's formulation of a specific investment plan. While the investment costs are used in the decision process, the amount by which the manufacturer actually carries the burden of this investment varies. The manufacturer may pay for the investment out of pocket but has a few options for passing those costs on to DoD. For example, the manufacturer can pass the investment costs directly to the DoD through value engineering change proposals (DoD, 2011; Mandelbaum & Reed, 2006) or indirectly through cost-of-money charges. Because there is no uniform treatment, the summary results on changes to the manufacturer's profit and government costs are presented both with and without the cost of making the investment.

Table 1 shows the manufacturer's additional profit due to investment in reducing unit costs for the baseline scenario that included 10% profit, a 2-year regulatory lag period, and 7% cost of money.

TABLE 1. MANUFACTURER'S ADDITIONAL PROFIT

		Without and with subtracting investment costs	
Program	**# Years**	**Without**	**With**
1	10	79%	27%
2	14	44%	0%
3	20	3%	0%

If the DoD pays for the investment, the manufacturer can increase profits by nearly 80% compared to the 10-year, endogenous-learning-only program. When the program is stretched the first time, the manufacturer's additional profit drops to about 45%. With the second stretch, additional profit increases by a few percentage points.

If the manufacturer pays for the investment, profits increase by about 25% for the 10-year program. When the program is stretched the first time, both the additional profit and incentive to invest are lost.

Table 2 shows the government's increase in procurement costs for the baseline scenario from stretching a program.

TABLE 2. CHANGES IN GOVERNMENT PROCUREMENT COSTS FROM STRETCHING A PROGRAM

Without and with investment costs

		TOTAL PROCUREMENT		CHANGE		CHANGE (%)	
Program	# years	Price	Plus Investment	Price	Plus Investment	Price	Plus Investment
1	10	6,426	6,772				
2	14	6,816	7,114	390	342	6%	5%
3	20	7,201	7,224	774	452	12%	7%

If the DoD pays for the investments to reduce unit costs, a stretch of 40% costs the government 5% of the total procurement costs, and a stretch of 100% costs the government 7%.

Both the DoD and the contractor lose money when programs are stretched because the contractor loses incentives to invest in cost-reduction initiatives and DoD loses their share of the savings.

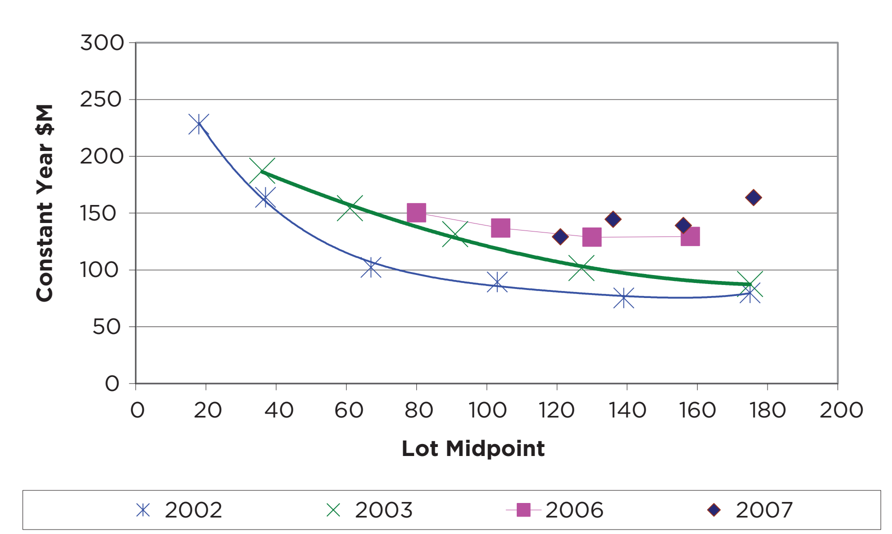
Remember that there are also increases in cost (not treated here) that are attributed to the additional fixed costs added to the program in the years into which the program was stretched.

Procurement Cost Data in Unstable Funding Environments

Actual procurement cost data that are available for the cost community to share are rare because of company proprietary rules. However, actual and projected average procurement unit costs are reported with the President's Budget and Future Years Defense Program and the Selected Acquisition Reports that are sent to the Congress annually.

Figure 4 shows the projected average unit costs as reported in 2002, 2003, 2006, and 2007 for the F-22 fighter procurement program, in constant-year dollars. The total projected quantity fluctuates between 160 and 180 units. The most obvious feature is the increasing projected average unit costs over time. Each successive learning curve is higher than the previous projections. The second most obvious feature is the flattening of the learning curves with each successive position.

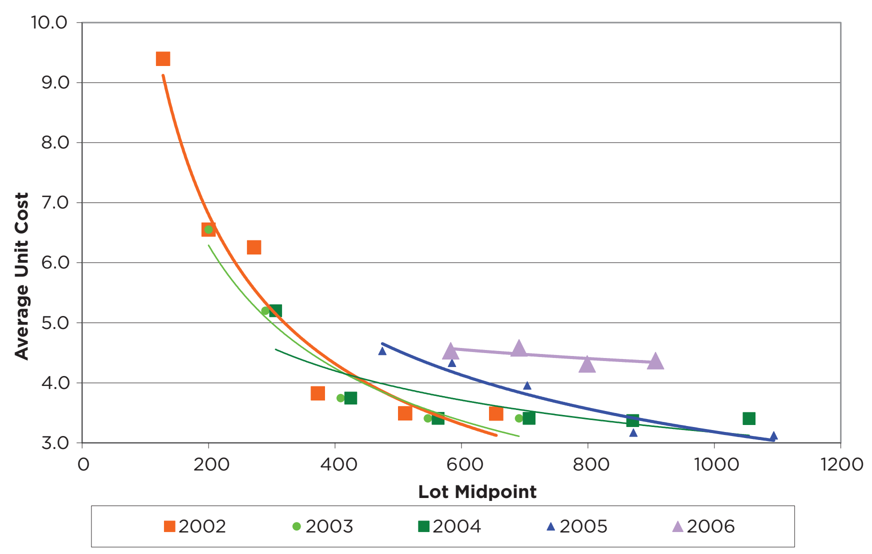
FIGURE 4. PROJECTED AVERAGE UNIT COSTS ON THE F-22 PROGRAM



A closer examination of the procurement data reveals that this program experienced several stretches in the procurement program, accompanied by decreases in the planned procurement quantity per year. Both the 2002 and 2003 President's Budget positions are 6-year programs, while the program is stretched to 7 years in 2006 and to 9 years in 2007.

The Phased Array Tracking Radar Intercept of Target (PATRIOT) Advanced Capability-3 (PAC-3) missile procurement program also experienced significant instability in planned procurement profiles. Figure 5 shows projected average unit costs by lot midpoint by the indicated President's Budget positions. While considerable scatter is shown around the trend lines associated with each position, several curves display clearly different slopes.

FIGURE 5. PROJECTED AVERAGE UNIT COSTS ON THE PAC-3 PROGRAM



If the only dynamics at work behind the projections in these two real-world examples were decreases in the quantity per year, the lot midpoint from series to series would be displaced up the curve to the left but remain on the same curve. If an additional cost per unit was being realized, the learning curve would be higher but maintain the same slope. The fact that the slope changes from one position to the next indicates another mechanism is in force, and that is the loss of economic incentives for the manufacturers to invest in cost-reduction initiatives.

Observations and Conclusions

This mathematical model was developed to provide a vehicle for quantifying the relationship between economic incentives and rate of exogenous learning on DoD procurement programs. It is not intended as a predictive tool.

Multiyear procurement contracts are one vehicle by which the DoD could control the length of the regulatory lag periods to increase the manufacturer's incentive to invest in cost-reduction initiatives. A long multiyear procurement is a contractual long regulatory lag, and the penalties for reneging on a multiyear procurement contract can be viewed as compensation for profit loss, both from the direct cost of the investments made and from the reduced future profits.

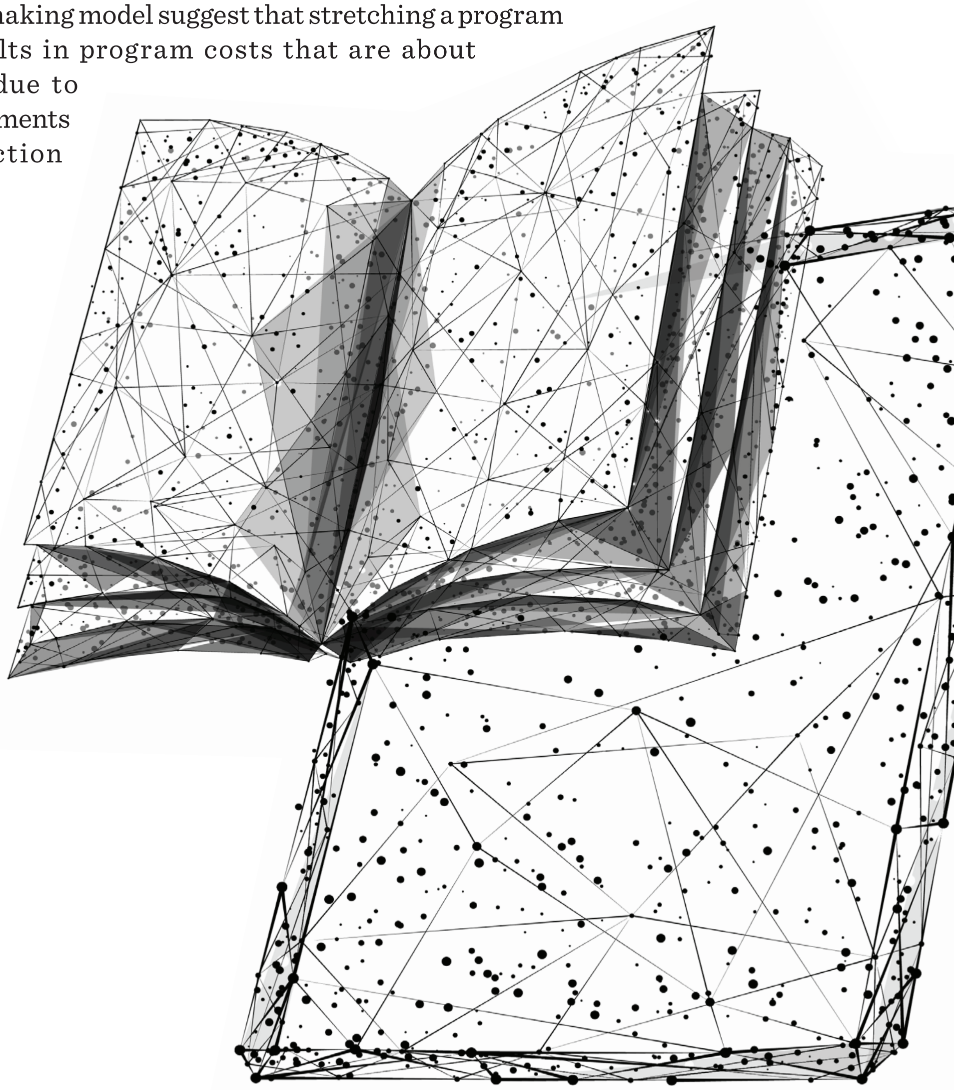
The results of the numerical experiments suggest that eliminating the regulatory lag period eliminates economic incentives for the manufacturers to invest in cost-reduction initiatives, thus increasing the cost to manufacture. The results also suggest that increasing the regulatory lag period increases the manufacturer's economic incentives by permitting the manufacturer to keep additional profit as a reward for lowering the cost. Increasing the regulatory lag period, however, has a diminishing return for the DoD because the government does not realize the cost savings until the end of the regulatory lag period. This result deserves more study to see whether there is an optimal solution that weighs government cost.

"It is readily accepted that stretching the planned buy profile (decreasing the quantity made per year while extending the length of the procurement program) increases the average unit cost of a procurement program because it adds a level-of-effort cost per year to the procurement program.

According to the results of simulations with this model, profit plays an important role in the manufacturer's incentive to reduce cost. When deciding to invest, the manufacturer is weighing the additional profit gained in the regulatory lag period against the projected profit loss in the years after the regulatory lag period.

The results of these numerical experiments look very much like the actual planned and projected learning curves for the F-22 and PAC-3 procurement programs, both of which experienced major changes to the procurement buy profiles.

In summary, it is readily accepted that stretching the planned buy profile (decreasing the quantity made per year while extending the length of the procurement program) increases the average unit cost of a procurement program because it adds a level-of-effort cost per year to the procurement program. This level-of-effort cost is incurred by the program in the years into which the program is stretched. It appears the DoD is paying an additional amount to stretch a program; these costs are incurred throughout the execution of the program and can best be described as changes in the slope of the projected learning curves. The experimental results of this decision-making model suggest that stretching a program by 100% results in program costs that are about 10% greater due to reduced investments in cost-reduction initiatives.



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