

IMPACTS OF ADVANCED MANUFACTURING TECHNOLOGY  
ON PARAMETRIC ESTIMATING

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I. INTRODUCTION

The introduction of advanced manufacturing technology in the aerospace industry poses serious challenges for government cost analysts. Traditionally, these analysts have relied on parametric estimating techniques for both planning and budgeting. Despite its problems, this approach has proven to be a remarkably useful and robust tool for estimating new weapon system costs. However, rapid improvements in both product and process technology could exacerbate current difficulties, and diminish the utility of the parametric approach. This paper reviews some weaknesses associated with parametrics, then proceeds to examine how specific aspects of the factory of the future may further impact parametric estimating, and suggests avenues of research for their resolution.

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<sup>1</sup>This paper is an extended version of "Cost Estimating for the Factory of the Future," published in *Flexible Manufacturing Systems* (Proceedings of the 3rd ORSA/TIMS Conference on FMS: Operations Research Models and Applications held at MIT, 14-16 Aug 89), ed. by Kathryn Steckle & Rajan Suri (Amsterdam: Elsevier Science, 1989, pp. 53-58).

## II. SOME PROBLEMS WITH PARAMETRICS

Parametric estimating is a method by which aggregated costs are derived as a function of high-level product characteristics or parameters. The resulting equations are known as cost estimating relationships (CERs). Such equations are particularly useful when detailed technical specifications are not available. For example, airframe costs have been found to be related to an aircraft's speed and weight (Eq. 1).

$$\text{Cost} = f(\text{weight, speed}) \quad (\text{Eq. 1})$$

A typical formulation might express cost as the product of speed and weight raised to some power. These parametric estimates are most useful as a planning tool while a program is still in the conceptual stage. Although such estimates are designed to give only a rough order of magnitude in accuracy, they are normally sufficient for examining performance tradeoffs and alternative force structures. Unfortunately, for lack of a better tool, these estimates often find their way into budgets where they tend to take on an aura of precision. Yet parametric estimates are anything but precise, as analysts must routinely violate the requisite assumptions, most typically, extrapolating beyond the range of data. Technically, the analyst estimating a new airframe may remain within the existing database for weight, and speed, although radically different design characteristics (such as composite materials or low radar cross section) can result in large estimating errors. Because the general trend is for new airframes to outperform the previous models, analysts are generally forced to make predictions on the basis of samples that are only roughly homogeneous.

To develop a CER, the cost analyst employs the statistical technique known as regression analysis. The goal is usually to develop a sound, logical relationship in which variance within the independent variables (performance, size, and programmatic parameters) "explains"

the variance in the dependent variable (e.g., cost). To achieve this end, the analyst regresses cost data for a similar class of weapons against logically-related weapon system characteristics. Typically, the analyst's major problem is finding a sufficient body of historical data for developing the CER. Developing the database is difficult for two reasons. First, newer generations of aircraft (or other weapons) are often vastly dissimilar from previous models. When higher costs cannot be fully explained between successive generations then analysts have greater difficulty estimating future weapon systems and justifying the estimates (still, adequate prediction is a satisfactory, though inferior, alternative to complete explanation). Second, data is becoming more scarce for newer generation aircraft as there are fewer types of aircraft built each decade and far fewer quantities procured of each type. For example, in 1951 the United States procured over 6,000 fighters compared to fewer than 300 in 1984, a time when the Air Force was well-funded (Sprey, p. 194). Similarly, the Air Force fielded six new fighters in the fifties, but only one (the F-117) in the eighties (Rich, p. 21).<sup>1</sup> Taken jointly, these problems make it exceedingly difficult to construct a large, homogeneous sample of weapons. Sticking with the aircraft example, the problem is exacerbated when the database is subdivided into mission type such as fighter, bomber, and cargo airframes. The limited data should also be normalized for varying accounting systems, varying contractor efficiencies and inflation, to name just a few problems. From this database the analyst then develops a CER by which to estimate the cost of an advanced weapon which probably has no equivalent in the current data set.

Naturally, this procedure violates a cardinal rule of regression analysis; not to extrapolate beyond the bounds of the current data. The extent of the error, if any, is a matter of degree depending on the variance of the proposed system from the data set as well as the

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<sup>1</sup>The process leading to only a few new starts and much smaller quantities has been referred to as structural disarmament. It is a result of conscious decisions to develop technically advanced systems in which quality is equated with effectiveness.

variance within the data set itself. When used as a planning tool as intended, this procedure has proven merit, but it makes a poor budgetary model (precise estimates are not possible in the early phase of an acquisition). In response, the estimating community has performed extensive research to improve the predictive ability of CERs.

Much of the research in estimation is in formulating new CERs or establishing better data bases. A more narrow avenue of potentially productive research focuses on the effects of evolving product and process technology on the estimating accuracy of existing CERs. To handle the problem of ever-advancing product technology, several models have proposed incorporating an index or factor which would attempt to distinguish the amount of technological advance over previous generations. Thus, where the analyst may have previously estimated cost as in Eq. 1, now she might account for a leap in technology with Eq. 2.

$$\text{Cost} = f(\text{weight, speed, technology}) \quad (\text{Eq. 2})$$

Given the stable manufacturing conditions which existed up to the eighties, such a model has intuitive merit. However, in the last decade, tremendous advances in manufacturing suggest an additional variable is needed to measure the manufacturing climate. One reason why costs are often underestimated even when new manufacturing is not taken into account is the inability to fully appreciate the level of technical difficulty some new weapon systems present. However, it is conceivable that the analyst who properly considers performance improvements but fails to consider the production environment could overestimate the cost of the new weapon. This manufacturing variable would have a negative sign because one would expect that military systems produced as recently as ten or fifteen years ago could be manufactured cheaper with the latest machining and process technology, although costs might initially be higher when new manufacturing equipment is first installed. For example, Herman Stekler found that if McDonnell Douglas could have produced the F-4 with manufacturing technology available for the F-15 fighter, the result would have been a 12.5 percent reduction in total

unit cost at the 155th unit. The difference in costs between the hypothetical F-4 (assuming unitized airframe components and direct numerical control machines) and the actual F-15 represented the improvements in quality and performance. When actual production man-hours (at the 155th unit) were indexed to 100 for both aircraft, the production index for the F-4 using new technology was estimated at 74. The relevance of this 26 percent decline is that the cost of performance enhancements is potentially greater than the absolute difference between the actual F-15 and F-4 unit costs in constant dollars. Theoretically, accounting for evolving manufacturing technology could significantly improve estimating accuracy. Thus, our hypothesized equation is revised as shown below.

$$\text{Cost} = f(\text{weight, speed, technology, manufacturing}) \quad (\text{Eq. 3})$$

Although no aggregate measures of manufacturing technology were found in the literature, several researchers have devised measures of technological change in military weapon systems. In some cases, a technological index may simply be a subjective number based on expert engineering judgment (e.g., in a RAND study, RM-6269-ARPA, Harman devised an A-Factor rating from 0 to 20), but more comprehensive measures are also possible. Another study by RAND (R-2249-AF) estimated the technological change in fighter aircraft and converted the composite index into a predicted first flight date, that is, the date that an aircraft possessing that particular set of performance characteristics would first be expected to fly as opposed to the actual first flight date. Assuming that this index accurately measures technological sophistication, then one might expect a regression of airframe cost against the variable's weight, speed and technology to result in a systematic (rather than random) residual pattern due to the failure to account for progress in the manufacturing environment. Because the error terms from a regression are the result of all factors not explicitly identified as independent variables, they are usually randomly distributed. For a systematic pattern to appear, the effect of

excluding manufacturing must be greater than all other influences combined. One such regression was constructed in RAND's Development and Procurement Costs of Aircraft (DAPCA, see R-3255) estimating model using empty weight (EW), max speed (SP) and the predicted first flight date (PFFD)<sup>2</sup> as independent variables for various categories of airframe cost in the typical logarithmic formulation:

$$\text{Cost} = a (\text{EW})^b * (\text{SP})^c * (\text{PFFD})^d \quad (\text{Eq. 4})$$

where cost is assessed separately in terms of engineering hours, tooling hours, and manufacturing hours. Although the overall regression results were significant (at .05) in all three formulations, there was no apparent pattern in the error terms to indicate a systematic bias due to overlooking manufacturing advances. While the hypothesis is logical in theory, the test may have failed because the residuals had little to do with manufacturing technology or possibly because of the weakness in the ability of the predicted first flight date to accurately assess intergenerational technological improvements apart from performance increases, or both.

Thus, the problem for the analyst remains how to make the technology and manufacturing variables operational in a parametric context. If developing an appropriate technology index is difficult, it is nearly impossible to quantitatively measure the state-of-the-art in manufacturing. Nevertheless, the characteristics of the contractor's physical plant have a definite impact on product costs. Figure 1 shows that costs will fall when product technology and performance are held constant. This is merely a theoretical extension of cost improvement curve theory which refers to continual production of a single design. Initially, unit or cumulative average costs fall as workers "learn" to do the job more efficiently. Eventually, learning flattens out over

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<sup>2</sup>The variable PFFD was eventually rejected from the recommended set of CERs in R-3255 as it added little predictive power, was highly correlated with performance variables, and was significant at the 5 percent level (individual coefficient) in only one equation.



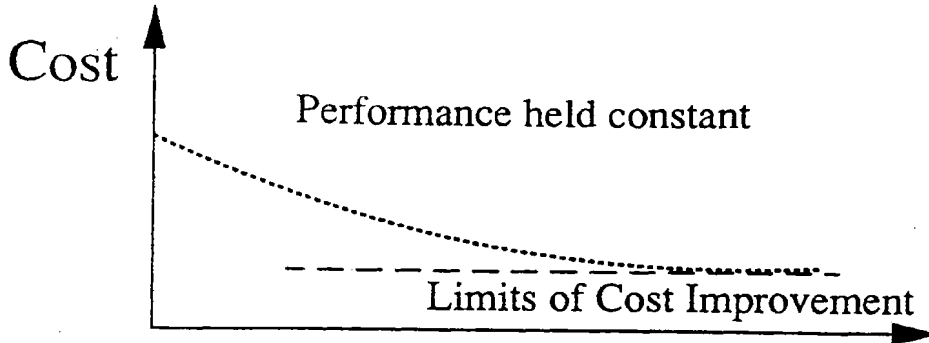


Fig. 1--Advances in Manufacturing Technology

time as both management and workers exhaust ideas for cutting costs. In the long run, however, one would expect a continued drop in costs as manufacturing technology advances. The limit of cost improvement, of course, is the cost of the raw materials, labor and capital to make the product because the product itself is held constant in this scenario.

Another way to look at the impact of manufacturing is in Figure 2. If the manufacturer is allowed to improve the product but not the process or capital equipment by which it is made, it again follows that in the long run costs must rise to account for the higher levels of performance desired between intergenerational models. Eventually, a point would be reached where no further product advancement could be made without altering the basic manufacturing process.

In the real world, both product and process are continually advanced. Figure 3 suggests that the increase in costs due to achieving state-of-the-art performance is usually greater than the decrease when

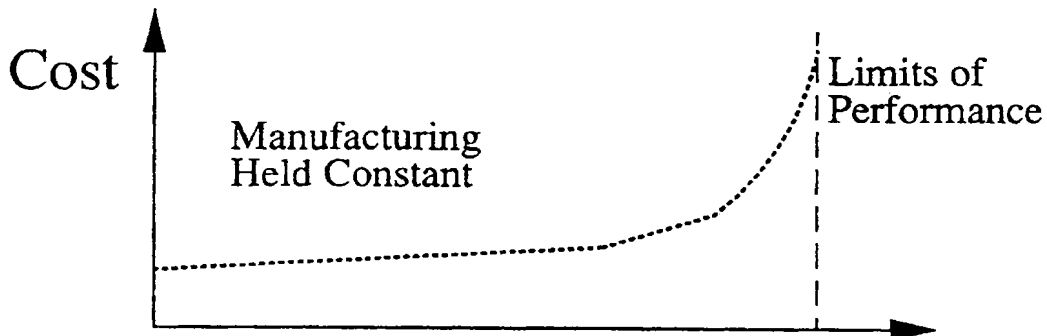


Fig. 2--Advances in Product Performance

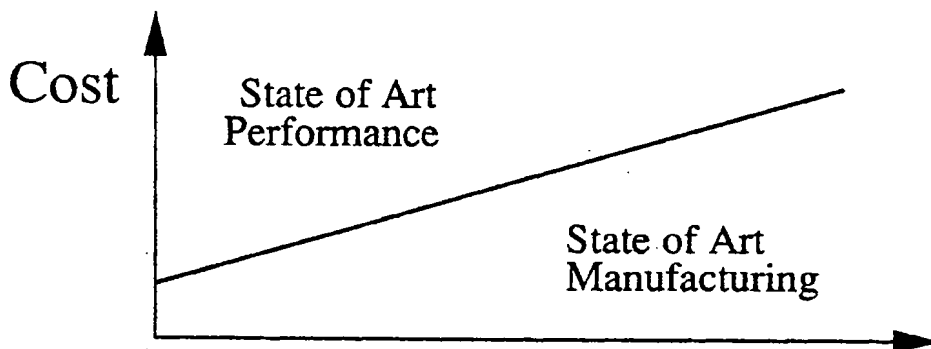


Fig. 3--Combined Result - Increasing Cost

the firm employs state-of-the-art manufacturing. Paul Killingsworth calls this phenomenon "performance push:"

This is the effect of operational requirements pushing engineers to design for the highest levels of functionality and performance allowed by current technology. Advances in design or manufacturing technology which could be interpreted as resulting in, for example, fewer required engineering hours, test hours, or parts to assemble, are usually more than offset by the increased complexity designed into the systems.

Another way of looking at cost performance tradeoffs of technology is shown in Fig. 4. In the short run, a new technology may follow the curve, Mfg Tech I. Performance improvements on a given curve are usually limited and costs may rise dramatically if practical applications for new design concepts are sought too early. As manufacturing technology matures, and the next short run curve is achieved (Mfg Tech II), a wider range of cost and performance opportunities becomes available. For instance, greater performance at nominally higher total costs is possible (per unit performance costs may fall but total investment costs almost always rise when seeking maximum capability). Other choices are also apparent from the graph. It is possible to increase performance somewhat at no additional cost, and of course, to achieve the same level of performance at lower cost. The time track drawn through the manufacturing technology curves is the one most often followed in defense procurement--namely greater performance at greater cost, despite tremendous gains in manufacturing know-how.

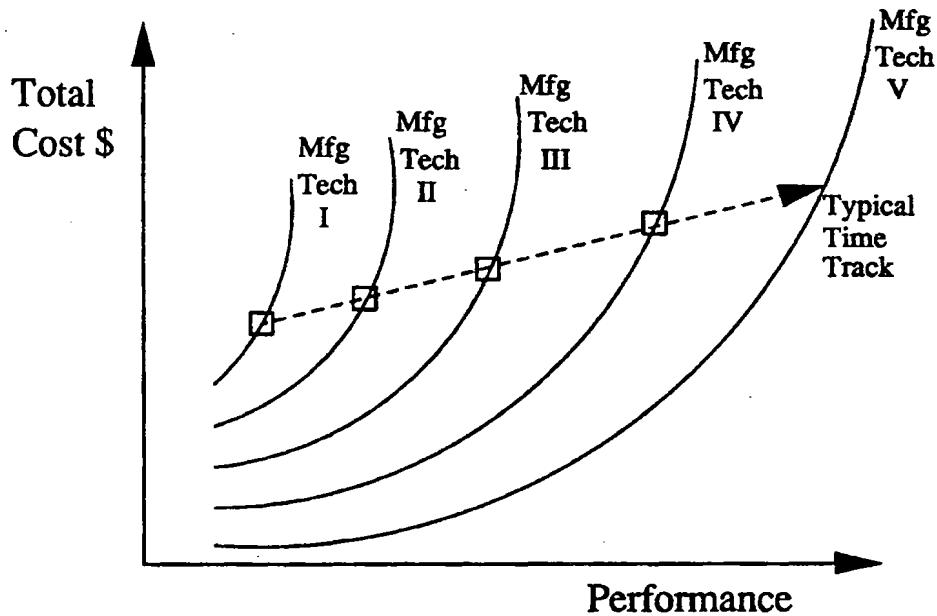


Fig. 4--Manufacturing Technology Curves

Finally, the graph implies that substantial improvements in performance, although not the best possible, could be had at lower absolute costs.

The specific shape of the short run curves would most likely vary for a given technology, and in the long run, most technologies would probably mature to the point where further investments are no longer worth the increase in output. This is not the case for advanced manufacturing technology which is relatively new. In short, manufacturing is an area that offers greater leverage for Air Force resources, and has potentially dramatic impacts on the state of cost analysis for military weapon systems.

Unfortunately, the data currently available to government estimators is not sufficiently detailed to distinguish the cost risk caused by product improvements from that caused by new manufacturing processes. Because advanced manufacturing technology is expected to reduce the real cost of pushing the state-of-the-art in weapon performance, one might conclude that the total cost uncertainty would be less, even if unintentional. However, recent experience hints that other effects of advanced manufacturing could adversely influence the best of parametric approaches. To better understand these effects, it

is first necessary to review what is meant by advanced manufacturing technology.

### III. WHAT IS ADVANCED MANUFACTURING TECHNOLOGY (AMT)?

AMT consists of a variety of new process technologies and management systems that, when implemented, have the potential to dramatically enhance a firm's design and production functions. The use of some elements of AMT in both the defense and civilian sectors has been called either Factory of the Future or Factory 2000. The ultimate goal of the more competitive firms is to achieve a fully automated capacity known as Computer-Integrated Manufacturing (CIM). CIM embodies many other elements of programmable automation along with various management information and microprocessor-based technologies. Some of the more common subsystems include computer-aided design and manufacturing (CAD/CAM), flexible manufacturing cells (FMC), and manufacturing resource planning (MRP). These new technologies represent three initiatives for increasing manufacturing productivity. These are the greater use of automated systems, the use of flexible tooling to increase product variety, and a concern with material flow to reduce inventory requirements. Most firms, however, have not been able, or perhaps willing, to completely redesign their production plants. Instead, the firm is more likely to progress in an evolutionary fashion through levels of AMT with increasingly greater sophistication (Meredith & Hill). In this view, a firm moves incrementally through five levels of automation, although skipping one or more levels is possible and may even be desirable. The five levels of AMT are:

- L0: Traditional Production Line
- L1: Stand-Alone Improvements
- L2: Cell Development (Islands of Automation)
- L3: Linked Islands (Continents of Automation)
- L4: Full Integration (World of Automation)

Starting with a basic production line, the manufacturer begins the automation process through the addition of robots and machine tools as stand-alone improvements. Eventually equipment is grouped into flexible manufacturing cells for the production of related parts. Level two is commonly referred to as islands of automation. When these islands are linked through a shared database (true CAD/CAM), level 3 has been reached. Finally, it is theoretically possible to completely automate the plant from top to bottom in concert with a management information system. Level 4 is most commonly known as computer-integrated manufacturing. While the technology exists to construct a CIM plant, it is widely believed that a true level 4 plant has not yet been build (Blois, p. 65). As firms move up the levels of automation, there is a large capital investment to acquire robots, computer numerically controlled (CNC) machine tools, cell controllers, and related equipment.

To achieve higher states of integration, eventually the firm must expend a greater share of resources on software and information technology. But the potential savings are worth the effort:

While it will take a decade or more to produce fully integrated CAD/CAM/CAS systems, any individual or collective improvements among them will pay immediate dividends in terms of better, lower-cost systems that are more easily manufactured, more reliable, and more supportable. This effort could potentially save the USAF billions of dollars each year in acquisition costs. (Forecast 2, p. 27)

The firm may invest for strategic (e.g., survival, new products, etc.) and economic reasons. Firms usually invest in capital equipment for reasons of efficiency. Some proponents of AMT argue that the equipment will pay-off in increased machine utilization. But others argue that the strategic opportunities afforded by AMT are paramount, while efficiency is only a secondary concern. For example, the shorter lead times, greater quality and flexibility which come from the proper use of optimized production techniques are essential to keep present customers, and more importantly, to find new ones (Pennar, p. 101). Companies on the leading edge of manufacturing innovation have experienced both types

of benefits. Nevertheless, it is the specific economic effects that most concern the cost estimator.

#### IV. ECONOMIC EFFECTS OF ADVANCED MANUFACTURING TECHNOLOGY

The savings and benefits that result from AMT are an unknown function of the level of automation and the specific industry involved. Nevertheless, the benefits of AMT over traditional production plants appear to be significant, although they may vary across product lines. The most prominent benefits are higher efficiencies achieved through direct labor savings, lower set-up times, and increased quality in the form of reduced scrap and rework. Another key enhancement due to CAD/CAM is reduced development time. With automated engineering drawings, it becomes much easier to make changes and design in producibility and maintainability. This benefit is very important to the civilian sector where product lifecycles are rapidly shortening. But reduced lead time can be highly beneficial to the military to shorten the weapons systems product cycle (perceived to be too long and growing)<sup>1</sup> and to allow rapid response to a changing threat. The use of new inventory systems such as Just In Time (JIT) and MRP produce direct dollar savings in the form of reduced work-in-progress, buffer stock and material inventory. Flexible manufacturing systems (FMS) also hold the promise of improving flexibility by allowing the production of variety without increasing unit cost. Theoretically, a firm with an FMS may eventually be able to economically produce varied (but related) lots of one-unit product. Altogether, AMT should enhance a firm's productivity and competitiveness in the marketplace.<sup>2</sup>

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<sup>1</sup>The perception of a lengthening acquisition cycle is strong but only a few quantitative studies exist. The Affordable Acquisition Approach Study concluded that "development time is significantly longer." M.B. Rothman suggests that there is some increase in the development cycle but none from FSD start to first delivery. He also notes that "grouping of systems before and after 1960 do not differ significantly."

<sup>2</sup>Specific benefits vary by product, cost element and type of installation. See *Towards a New Era in U.S. Manufacturing* (pp. 118-119) for representative productivity enhancements of FMS and CIM technologies.



The ability to directly measure the savings associated with implementing AMT tends to decrease as the firm moves to higher levels of automation. When a firm invests in level one and level two technologies such as robots and CAD, the savings in direct labor are usually tangible. Therefore, level one and two technologies can be justified with traditional return on investment (ROI) measures such as payback period or the internal rate of return (IRR). However, many of the benefits of level three and four technologies are intangible or, at the least, very difficult to quantify. The problem for the estimator is that the bulk of the historical cost database lies in levels L0 (traditional) and L1 (stand-alone improvements). As firms automate at higher levels, cost uncertainty increases due to decreased ability of existing data to explain and predict new cost patterns. Of the many potential effects due to AMT, the reduction in direct labor and a probable flattening of learning curve could have the greatest impact on the cost estimator.

**Direct Labor Reductions:** Reductions in direct labor are not new to the aircraft industry, where extensive hands-on labor has been necessary for assembly and other operations. In the airframe industry (Standard Industrial Class. 372), production workers accounted for 74.5 percent of total labor in 1951, but only 47.7 percent by 1985. As a result, direct labor costs now only account for a small percentage of total program costs.<sup>3</sup> No change in this trend is expected due to increasing installation of robots, flexible systems and CNC machining which have made tremendous improvements in part-making and assembly operations. In fact, in a few highly-automated plants, total direct labor has fallen to

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<sup>3</sup>To test this, four aircraft (A-3D, F-4D, F-89C, and F-105D) with first production acceptance dates between 1950 and 1960 were selected. Summing the contracts until quantities were near 200 revealed that direct labor dollars ranged between 33.1% and 36.9% of the total contract cost (airframe line). These aircraft had similar production rates as the A-10A, F-14A, F-15A and F-16A with acceptance dates in 1972 or later. Direct labor accounted for 24.8% to 27.6% of total contract costs on the airframe line for the latter sample. Aircraft data for the eighties is scarce, but five contracts on four aircraft reveal a range of 18.6% to 23.6% of direct labor costs to total costs.

a point that it is no longer worth tracking as a direct cost element. Moreover, treating low levels of direct labor as an indirect expense can save hundreds of thousands of journal entries. However, the majority of firms are still constrained by traditional cost accounting systems which were established in the early years of mass production to tightly control direct labor. The new manufacturing environment is making many of these cost systems obsolete if not dysfunctional.

The declining importance of direct labor as a measure of operational control has significant impacts on many facets of a firm. Typically, indirect expenses are accumulated in large cost pools and distributed to cost centers based on direct labor dollars or hours. As direct labor shrinks relative to indirect cost, burden rates have grown disproportionately large. The current system penalizes labor intensive operations versus more heavily automated cost centers when new machines are depreciated to common overhead pools. Some of the adverse consequences are:

1. Production engineers may overdesign automation into a given process to avoid excessive overhead charges that a labor intensive, but perhaps cheaper, operation would bring. This is a subtle but important argument because the more frequent problem is justifying new processes with outmoded ROI measures.
2. Make or buy decisions may be skewed towards outside purchase as cost centers suboptimize to avoid labor-based overhead. The decision to subcontract further exacerbates the problem because existing overhead is then applied to a smaller labor base.
3. The focus on tracking only direct labor and material can widely distort true product costs and profits. Strategic decisions based on incorrect data can lead to manufacturing decline, and ultimately, business failure.

For the estimator, the potential failure of standard cost systems (job order and process costing) in the factory of the future has profound implications, particularly given that current weaknesses have

not been adequately resolved. A major criticism of parametric estimating has been that past inefficiencies recorded in the cost accounting data (overruns, waste, excessive manpower, etc.) are carried forward in the estimate of the new weapon system. But this criticism may not go far enough. Traditional cost accounting systems, especially in a multi-product firm, may not even remotely measure true costs regardless of efficiency. In one study by Robert Kaplan, "a more accurate system revealed that products yielding healthy profits according to the standard cost system--with indicated margins of more than 45 percent--were actually losing money," (Kaplan, 1988, p. 64). Thus, as labor costs diminish in size relative to total costs, CERs used to predict labor costs may lose their utility as an important element of current cost models. For example, many CERs use various categories of labor hours (e.g., manufacturing, engineering, etc.) as independent variables. This allows the analyst to remove the effects of inflation from historical costs and to simply apply current labor rates to determine present costs. However, in building up to the total cost estimate, various overhead and other cost factors are applied to the labor-hour base. As the direct labor base diminishes, the likelihood of misestimating the labor hours on new weapons is increased; and the total impact of misestimating direct labor is magnified in the final estimate (due to greater overhead rates and a smaller base). In short, it is difficult to estimate the total costs of a new system from direct cost CERs that only represent a small fraction (say, less than 20 percent) of the final investment. Because indirect costs account for the bulk of total system costs, investments in AMT should focus on these cost elements as well. Likewise, cost estimating will have to expand from its focus on direct labor and materials. Until this emphasis is changed through new methodologies, it will be important to understand the precise impact of AMT on recurring costs.

Eventually, the proportion of direct labor to total costs could fall so low that the continued use of labor hours as the standard base for aerospace cost accounting would be in serious jeopardy. At some point, the decision to continue using direct labor hours or dollars as

an allocation base will become totally arbitrary. Then the need for a new accounting system will be widely apparent. A number of researchers are already working this problem and have proposed to replace antiquated cost accounting systems with cost management systems. A specific example of a cost management system is activity-based costing which proposes to do away with notions of fixed and variable costs, due to their diminishing relevance. The shortcomings of traditional cost accounting are described by Kaplan:

With the new organization and technology of manufacturing operations, variable direct labor and inventory are vanishing from the factory... Existing cost accounting systems will become even more obsolete as companies invest further in computer-integrated manufacturing processes. With this technology, almost all relevant manufacturing costs become fixed costs; in fact, they are not only fixed, they are largely sunk costs, because the expenditures on the equipment and on the extensive software required to operate this equipment must be incurred before production can ever begin. (Kaplan 1985, p. 220)

Activity-based costing proposes to counter this trend by moving away from fixed and variable classifications to those that are traceable or nontraceable. To determine traceability, internal studies must determine what is feasible. Technology costs such as depreciation, machine maintenance, utilities and operator training are examples of significant, traceable costs that have historically been relegated to overhead pools (Prior, 1989). For the cost analyst, the new accounting could drastically alter parametric estimates because costs could be attributed to manufacturing processes rather than product features. Two other points are also important to note. First, this is a long term problem. Traditional cost accounting systems will not change overnight due to numerous impediments. Financial reporting, government tax requirements, the Cost Accounting Standards, DoD Cost/Schedule Control Systems Criteria, and organizational resistance will most likely result in evolutionary change. Accordingly, the near-term problem for analysts is the lack of relevance due to an old system grafted onto a modern plant. As one author cautions,

Blind adherence to traditional cost systems will result in expensive inefficiency and inaccuracy in estimating product costs. (Kim, p. 31)

The second point worth noting is that cost accounting systems will eventually change, although probably at a slower pace than required by FMS and CIM technology. Manufacturing systems that result in dramatically shorter process flows, far fewer cost centers, and a de-emphasis on indirect cost pools (in favor of simply production and period costs) usually result in simpler, less detailed ways of measuring cost. As defense firms update their systems, databases including costs from more than one contractor will have to be carefully constructed to ensure commonality of cost elements. Again, the result is increased risk in future estimates. For the cost analyst, the changing manufacturing environment presents a double-edged sword. Traditional cost systems may not reflect true product costs, and new cost systems may diminish or even eliminate the utility of older databases.

**Flatter Learning Curve:** The use of AMT is also expected to impact the application of learning curve theory in cost estimating. Again, how much so depends on the degree of automation and its proper utilization. Nevertheless, there should be a diminished opportunity for workers to learn better ways of accomplishing a task, primarily due to the reduction of direct labor. In addition, elements of learning due to improvements in tool coordination, shop organization and inventory systems will be eliminated by the ability to simulate production processes and layouts prior to setting up a plant (Wild, 1987). Although it is difficult to believe that all learning will end, the combination of some of these effects could dramatically alter conventional thought about the expected slope and behavior of cost-quantity relationships in given product categories. In fact, some researchers predict that the standard cost point (the quantity at which no further learning takes place) may fall to less than 100 units by the year 2000 (Selzer, 1986). Because total costs are so sensitive to the slope of the learning curve, labor hours are often estimated for production of the 100th unit. Application of the expected slope then

yields the predicted cost of the first unit, known as T1. If the analyst uses a "typical" industry curve derived from historical data, the result may be a much steeper curve than could be realistically expected in a modern plant. But the first production unit in a factory of the future (*ceteris parabis*) should start with a significantly lower T1, such that cumulative costs are much lower despite the flatter curve.

By correlating learning curve slopes for airframe data from RAND's DAPCA model (R-3255-AF) it was possible to test the hypothesis that reductions in labor and automated processes are lessening the impact of production experience. The DAPCA database consists of 34 different airframes (including 17 fighters) with first flight dates ranging in time from 1948 to 1978. Specific slopes were available through the 200th unit (proprietary data) for the total program, engineering hours, tooling hours, manufacturing hours, and manufacturing material dollars. The expectation was that a shallow slope (*i.e.*, less learning) would evolve over time yielding a positive correlation. The results for both the total sample ( $n=34$ ) and the fighter subsample ( $n=17$ ) indicate otherwise.

Table 1. Direction of Correlation Coefficients Over Time

Learning Curves				
Total Program	Eng Hours	Tooling Hours	Mfg Hours	Mfg Material
Fighters - (sig)	-	-	+	-
Total - (sig)	-	-	+	+

The correlation analysis showed that with the exception of manufacturing hours and manufacturing material (total sample only), slopes have been getting steeper. That is, more learning is taking place through unit 200 now than earlier. However, none of the slopes yielded results significant at the 10 percent level except for total program costs (.05 for all airframes and .10 for fighters).

There are several explanations for this seemingly counterintuitive result. One problem lies with the data itself, which is heavily skewed towards fifties technology. Of the 34 airframes in the total database, 21 had first flight dates prior to 1960 and only six first flew in 1970 or later. No data for the eighties was available. Although the Air Force sponsored the development of numerical control machines, the diffusion of more advanced technology is still a relatively recent phenomenon. The paucity of new airframe starts in the last fifteen years precludes an industry-wide analysis at the very time AMT is penetrating industry practice. Another issue masked by the data is the point in time at which a particular firm implements new equipment and methods. The hypothesis assumes that equipment is in place prior to production and that the firm has used a model shop, simulation techniques, or some other method to test the work flow. If new, successful process changes are made during production, a steeper learning curve should result in the aggregate. Of course, a third possibility is that the hypothesis is simply wrong. Discussions with other researchers in flexible manufacturing systems indicate divergent views on what may happen. Some argue that although there are fewer workers in these types of plants, each worker has greater control on the process and thus "learning" can result in widespread rather than narrow improvements. Still others suggest that FMS will result in a sharply steeper learning curve initially, but turning flat very early in the production run. Figure 5 shows some of these hypotheses pictorially. Either formulation (H1 or H2) results in lower costs. The questions that need to be answered for costs analysts are 1) will AMT impact the first unit cost, T1; 2) will AMT result in a flatter learning curve or dramatically steepen it as others propose; and 3) will the standard cost point be reached significantly sooner. Research focused on these areas is needed to sort out the specific effect.

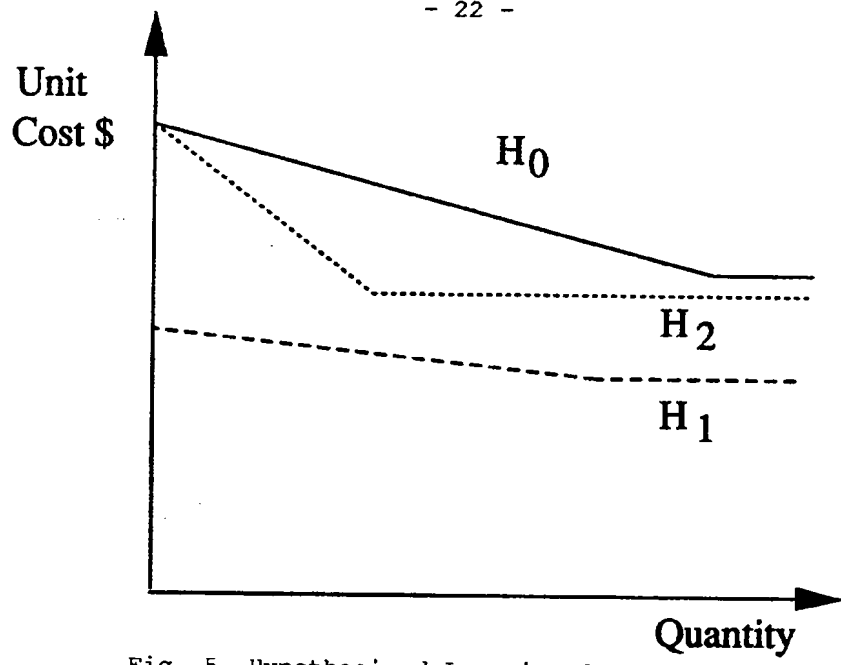


Fig. 5--Hypothesized Learning Curve Impacts



**V. A HYPOTHETICAL EXAMPLE OF ESTIMATING UNCERTAINTY**

A simple example should suffice to demonstrate the potential for error that the new manufacturing environment poses. Suppose that based on a heterogeneous sample of 1960s and 1970s military aircraft, the Department of Defense estimates that a new close air support (CAS) aircraft for the 1990s would require a cumulative average of 200,000 direct manufacturing labor hours at the 100th unit. Past experience suggests that an 85% cumulative average cost-quantity slope is appropriate. The estimator must determine the total manufacturing labor cost for 250 aircraft assuming a fully burdened labor rate of \$60 per hour. This problem can be solved with the following two equations:

$$Y = AX^b \quad \text{(Eq. 5)}$$

where Y = Cum average cost

A = Cost of Unit 1    X = Unit number

b = Learning curve exponent

$$b = [\text{Log}(\text{Slope})]/.301 \quad (.301 = \log 2) \quad \text{(Eq. 6)}$$

Therefore,             $b = [\text{Log}(.85)/.301] = -.234$

By substitution,     $A = 200,000/(100)^{-.234} = 588\text{K hours}$

$Y_{250} = 588 (250)^{-.234} = 161.5\text{K hours}$

Total Hours = 250 Aircraft X 161.5K = 40,375K hours

Manufacturing Labor Cost = \$60 X 40,375K = \$2,422.5 million

However, the prime contractor awarded the CAS contract has a flexible manufacturing system with a true CAD/CAM shared database. Prior to the plant conversion, manufacturing labor was consistent with that predicted by the DoD estimating relationships. However, the advanced technology in place has reduced labor by 20 percent such that in reality the cumulative average manufacturing labor hours should be 160K at the 100th unit. In addition, the ability to simulate the plant

layout meant the actual experience curve was only 90 percent through the 100th unit and flat from there on.

Thus, total costs are calculated as shown:

$$b = [\text{Log}(90) - 2] / .301 = -.152$$

$$A = 160,000 / 100^{-.152} = 322\text{K hours}$$

$$\text{Unit Cost } Y = 322[(100)^{1-.152} - (99)^{1-.152}] = 135.7\text{K Hours}$$

$$\text{Total Hours Through Unit 100} = 100 \text{ units} \times 160\text{K} = 16,000 \text{ Hours}$$

$$\text{Total Hours Units 100 to 250} = 150 \text{ units} \times 135.7\text{K} = 20,355 \text{ Hours}$$

$$\text{Total Hours} = 36,355 \text{ Hours}$$

$$\text{Manufacturing Labor Cost} = \$60 \times 36,355 = \$2,181.3 \text{ million}$$

The difference is \$241.2 million or almost a 10 percent reduction in costs assuming no change in the overhead rate.<sup>1</sup> Indications are that total indirect costs should also decline in a fully integrated environment, but this requires further empirical verification. Obviously, this is a contrived example; and the defense community has a greater problem underestimating costs than vice versa. The reason for this is the "performance push" phenomenon noted earlier. But, if performance could be held constant, then CERs based on historical data are likely to overestimate total costs in an advanced manufacturing plant. The key to maintaining the utility of parametric methods is for the analyst to be able to distinguish between the effects of advancing product and process technology. This much is imperative. Thus, a fixed burden rate implies lower indirect costs as well.

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<sup>1</sup>If indirect costs were fixed, the burden rate would have to rise on a labor hour basis due to lower direct labor hours.

## VI. SUGGESTED RESEARCH

Assessing the state of manufacturing in the aerospace industry is a necessary first step. How does the defense establishment compare with commercial firms? Do prime contractors invest more heavily in advanced manufacturing than subcontractors and their vendors? Are contractors investing uniformly? The obvious hypothesis is that the level of automation varies between defense and non-defense firms, and within the various tiers of the defense industrial base. Were this not true, a simple time index could be incorporated to indicate the advent of major new manufacturing advances such as CAD/CAM. Because manufacturing methods were largely static prior to the eighties, even a dummy variable might suffice to distinguish a data set. An industry-wide survey is a must.

To accomplish the survey, a framework for categorizing the level of automation in a firm is necessary. Such a framework should be sophisticated enough to handle the variety that is certain to be found, and yet conducive to quantification in the form of an index.

Cost database managers should collect manufacturing information for research purposes. Similarly, analysts may wish to repeat previous cost regressions with the addition of a manufacturing index. Perhaps most important is to quantify the effects of programmable automation. What are the average engineering, tooling, manufacturing, etc., labor hours in plants producing similar equipment but with varying degrees of manufacturing technology? Does AMT reduce costs immediately or do costs rise at first then fall as the technology matures? Has AMT reduced indirect labor as well, or is it generating a greater requirement for knowledge workers? Are average labor rates higher in the more advanced firms? Cost analysts with access to such data could further their profession by finding the answers to these and other related questions.

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