Improvement Curves: An Early Production Methodology

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Abstract: Learning slope selection is a critical parameter in manufacturing labor estimates. Incorrect *ex ante* predictions lead to over- or understatements of projected hours. Existing literature provides little guidance on *ex ante* selection, particularly when some actual cost data exists but the program is well short of maturity. A methodology is offered using engineered labor standards and legacy performance to establish a basic learning curve slope to which early performance asymptotically recovers over time.

Introduction

Manufacturing labor hours are often the largest single category of direct labor cost, particularly for initial or follow-on production programs. Manufacturing hours are typically estimated by improvement curves projected from a theoretical first unit cost to calculate hours for a given block of units. It follows that the choice of an improvement curve slope is a critical parameter in accurate estimates. Moreover, because manufacturing labor hours are often used as a base in cost estimating relationships to project other functional hours (such as quality assurance or sustaining engineering), an error in a manufacturing estimate is frequently compounded.

Surprisingly, learning curve literature offers little guidance on the *ex ante* selection of learning curve slopes. At best, studies authored by RAND or other research groups offer industry averages derived from empirical data collected from historical programs. The literature offers this to the estimator when no actual cost data is available on the current program being estimated: the assumption being that a historical average provides some valid guidance for slope selection. In the case where at least some actual cost data from the current program is available, however, the literature goes silent. The prevailing assumption seems to be that the improvement curve slope established from the current program's actual data accumulated to date will simply continue into the future with little or no change.

In fact, neither of these assumptions is warranted. Regarding the first case – the use of an industry average – Dutton (1984) cautioned:

"In general, the empirical findings caution against simplistic uses of either industry experience curves or a firm's own progress curves. Predicting future progress rates from past historical patterns has proved unreliable." (p. 237)

Similarly, Fox, *et al.* (2008) cited:

“Even with both an excellent fit to historical data (as measured by metrics like R^2), and meeting almost all of the theoretical requirements of cost improvement, there is no guarantee of accurate prediction of future costs.…[E]ven projections based on producing an almost identical product over all lots, in a single facility, with large lot sizes, and no production break or design changes, do not necessarily yield reliable forecasts of labor hours.” (p. 94)

But more discouraging news awaits. Regarding our second case – using actuals from early production lots to forecast subsequent lots -- Fox, *et al.* continue:

“Out-of-sample forecasting using early lots to predict later lots has shown that, even under optimal conditions, labor improvement curve analyses have error rates of about +/- 25 percent.” (p. 94)

It takes only a bit of sobering math to see the potential consequences of erroneous improvement curve selection. For example, if the estimator predicts a 75% improvement curve slope, but the program achieves only an 80% slope, the estimated hours will be understated by 59% by the time the 150th unit is built.

The generally poor record of historical cost performance to estimates by Department of Defense (DoD) programs suggests that these type of estimating errors are not infrequent, and that they generally tend to understate the required costs**.** The General Accounting Office (GAO) determined 98 Major Defense Acquisition Programs from FY2010 were collectively $402 billion over budget since their initial cost estimates. A root cause analysis of 104 MDAPs by the Center for Strategic and International Studies reported inaccurate cost estimates alone are potentially responsible for 40 percent of the accumulated overruns (Hofbauer, 2011). This suggests that improvements in estimating methodologies – including but not exclusive to improvement curve slope selection -- are badly needed. However, this deficiency is almost completely ignored in the existing learning curve literature. Reading that literature, one would suppose that the most pressing problem faced by the estimator is his choice of unit cost vice cumulative average theory, or how to establish a representative midpoint for lot cost data. As if our problems were so easy!

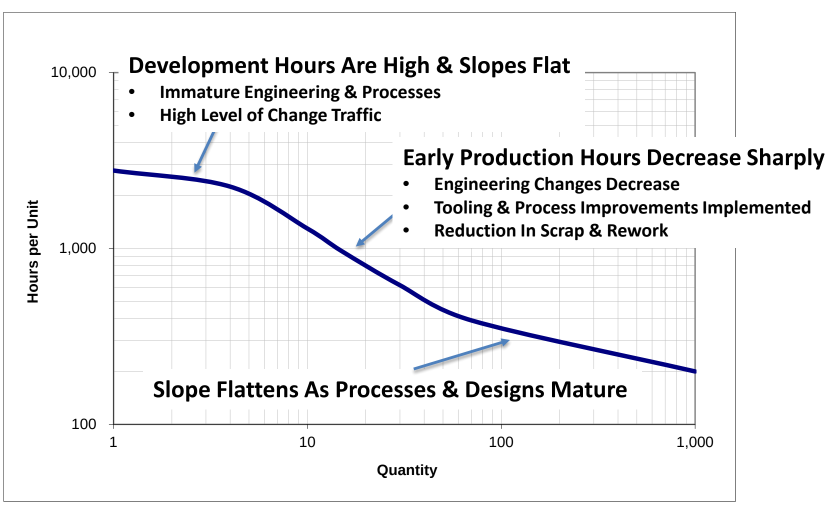
The purpose of this paper, then, is to suggest a heuristic methodology intended not to solve the problem of *ex ante* selection but at least bound it. It proposes to look at the choice of improvement curve slopes during a particularly challenging time period: that is, early in the program when limited actual cost data is available and manufacturing processes are still maturing.

Underlying Patterns of the Learning Curve

The initial learning curve studies (Wright, 1936, Crawford, 1944) understood improvement curves as straight-line logarithmic functions. Within a few years, however, observers began to see improvement curves not as straight lines in a log-log space, but curvilinear functions that exhibited an "S" shape based on product and process maturity (Carr, 1946, Asher, 1956).

The S-shaped improvement curve as commonly drawn is composed of three stages, captured graphically in Exhibit 1. The first stage, typically in the product development phase, shows high hours per unit and

Exhibit 1. Profile of the S-Curve



relatively flat improvement curve slopes. The limited degree of improvement is caused by an evolving engineering design and immature manufacturing processes. Part shortages disrupt the continuity of production. Scrap and rework is high, and there are typically a high number of engineering changes.

In the second stage, typically during early production, the hours per unit decrease sharply along a relatively steep improvement curve. The production rate increases significantly from the relatively low delivery rates of the development phase. Engineering changes decrease sharply, while improvements in tooling and manufacturing processes are implemented. Manufacturing scrap and rework also decreases at a faster rate. Shortages decrease as the supply chain begins efficiently feeding the production line.

In the third stage, production rates continue to increase to their maximum build rate. Manufacturing processes, tooling and engineering designs mature. Consequently, the pace of production improvements slow and the learning curve slope flattens in response.

Cochrane (1960) suggested S-curves have an underlying “basic slope” – that is, although the hours per unit captured in the S-curve may be higher or lower at a given point, the curve itself tends to regress to a mean “basic slope.” Referencing Exhibit 2, in the initial phase of the S-curve the early unit cost is higher than that indicated by the basic slope. After the initial engineering and tooling issues are resolved, the S-curve recovers to the basic slope. Cochrane believed that crossover point occurs at unit 30; in the author’s experience, the crossover point occurs closer to unit 80. The S-curve continues beneath the basic slope until the two lines intersect again at some future point. Cochrane, whose background was aircraft production, assumed this point to be unit 1000.

Exhibit 2. Relationship of Basic Slope to the S-Curve

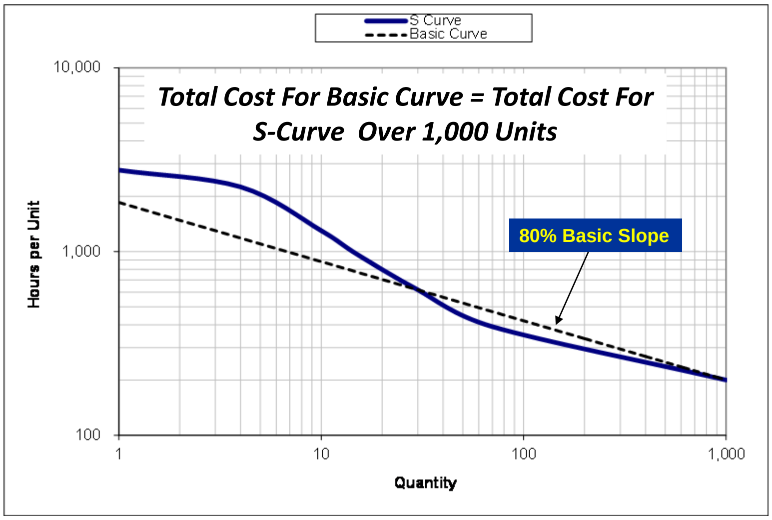


Exhibit 3 captures typical "basic slopes" identified from various sources. All are consistent with the industry averages captured in a variety of improvement curve studies (Cochrane, 1968, Delionback, 1975, Kassapoglou, 2013).

Exhibit 3. Typical Basic Slopes

Typical 'Basic Slopes'	Slope %	Source
Job machine shop	95%	Cochrane
Sheet metal stamping	92%	Cochrane
Composites automated layup	92%	Kassapoglou
Electrical fabrication	90%	Delionback
Job machining – large parts	88%	Cochrane
Electronics subassembly	85%	Delionback
Composites handlay	85%	Kassapoglou
General subassembly	83%	Cochrane
Major aircraft assembly	80%	Cochrane

The relationship of the basic curve and the S-curve can now be expressed more formally. The familiar formula for the unit theory cost improvement curve (Crawford, 1944) is expressed as

$$y_i = ax_i^b$$

where y = hours to manufacture unit i, x represents cumulative output, a is the theoretical first unit hours, and b defines the slope of the improvement curve.

Converted to a linear function in a log-log space, this becomes:

$$\ln y_i = ln\ a + b \ln x_i$$

Equally familiar is the unit theory formula for cumulative Y hours for n units from unit 1 through unit i, as represented by:

$$Y_n = a \sum_{i=1}^{n} x_i^b$$

The S-curve can be expressed in a variety of mathematical formulations, such as a cubic function in the form:

$$y_i = a + b{x_i}^3 + c{x_i}^2 + dx_i$$

where y = hours to manufacture unit i and x represents cumulative output (Miller, 1971). Expressing this as a cubic function in a log-log space yields:

$$ln\ y_i = ln\ a + b(ln\ x_i)^3 + c(ln\ x_i)^2 + d(ln\ x_i)$$

Given this, the formula for cumulative Y hours for n units from unit 1 through unit i is:

$$Y_n = a \sum_{i=1}^{n} e^{[b\ (\ln x_i)^3 + c\ (\ln x_i)^2 + d\ (\ln x_i)]}$$

Cochrane's proposal can now be stated formally – that is, that the total cost of the basic curve equals the total cost for the S-curve over a sufficiently large number of n units, in this case 1,000 units:

$$Y_n = a \sum_{i=1}^{1000} x_i^b = a \sum_{i=1}^{1000} e^{[b\,(\ln x_i)^3 + c\,(\ln x_i)^2 + d\,(\ln x_i)]}$$

The Use of Industrial Engineered Standards

To return to the earlier scenario outlined at the beginning of this paper: it is in early in the production phase of a program and there is limited actual cost data. That data shows relatively limited learning to date. Evidence from the shop floor indicates that there is substantial room for improvement – there are significant numbers of shortages which have caused delays and "workarounds" waiting for parts, scrap and rework ratios are high – but a number of improvements have been implemented and management expects the hours per unit to begin dropping significantly in response. Meanwhile, government contract negotiators are complaining about the program's "poor performance" and comparing the experience to date to improvement curve slopes from other historical production programs. They insist that the program's experience to date is not reasonable to project forward, and that the program should be entering into a "recovery curve" that will significantly reduce hours per unit by the time work begins on next production lot under negotiation. The program estimating team agrees, but at the same time it is uncomfortable with the projected slope that the government has put forward. The team is also uncomfortable with the short period of time over which the government projects this recovery to occur.

The estimator's dilemma can be reduced to three questions:

1. What kind of 'to-go' slope can we expect?
2. How long will the steep phase last?
3. What are we recovering to, and how quickly?

Without an analytical framework, these questions cannot be answered except by reference to other historical programs (all of which show different recovery slopes occurring over different periods of time) or the estimator's best judgment, which naturally diverges from the best judgment of the government negotiators.

This paper suggests the concept of the S-curve can be married to industrial engineering labor standards to help establish the end point of the basic curve and allow more accurate prediction of future costs.

The conventional definition of a standard is the time necessary for a qualified workman, working at an efficient pace and experiencing normal durability and delay, to do a defined amount of work of a specified quality using standardized processes and procedures. MIL-STD-1567A (1983) defined two types of standards: Type I, an engineered standard defined by an engineering time study (for example, 4M) or work sampling; and Type II, which covers all other kinds of standards established by different means (task center averages, engineering estimates, et al.)

The advantage of a Type I standard is it provides an objective measure of the true work content. The variance between the standard and actual hours is a reflection of the efficiency of the shop floor, and is to a large degree dependent on our position on the improvement curve. Early in the program the variance between actual and standard will be high, reflecting many of the production issues the program faces (high scrap and rework, delays due to late engineering or shortages, et al.) That variance will reduce over time as manufacturing processes, engineering and tooling improve and workers become more familiar with their task. In the aerospace industry for instance, with its long cycle times and constant product improvements, it is unlikely that shop performance will actually equal, much less go below, the standard. Exacting quality specifications insure that scrap and rework will never be completely eliminated, part shortages will continue to exist albeit at a lower level, and there will always be some degree of inefficiency caused by the introduction of engineering changes or product redesign.

But it is not necessary for our purposes that actual hours eventually reach standard. The point is that a Type I standard establishes a “floor” below which actual hours (or estimates) cannot go.

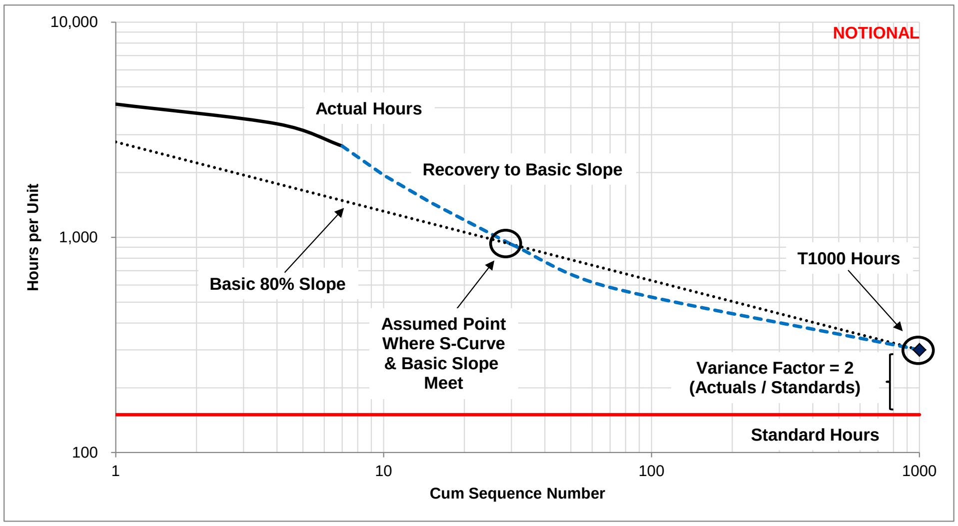
With cancellation of MIL-STD-1567A, the use of Type I standards for estimating purposes is no longer required. However, many large companies continue to use standards for the purpose of measuring shop floor performance. One of the reasons for the cancellation of MIL-STD-1567A was the significant amount of manpower required to create and maintain Type I standards. Fortunately, advances in computer technology allow the easier application of predetermined Type I standard templates based on certain parameters (number of fasteners, linear inches of sealant to be applied, etc.) applied against production planning cards. Software tools such as Lockheed Martin Aeronautics’ Engineered Time Standards / Manufacturing Analysis Package (ETS / MAP) allow Type I-quality standards to be established much earlier in the program life cycle using considerably less manpower than the old manual time-study or work sampling approaches.

It is not necessary for this methodology that the standard be strictly defined as Type I under the MIL-STD-1567A rubric. It is only necessary that: (a) the standard be a true representation of work content, (b) that it be applied consistently across the product, and (c) that we can reliably establish from legacy programs the expected performance to that standard at some point in the future, i.e., when the product and processes reach a point of maturity.

Let us assume that our legacy production history establishes that this point of maturity occurs at or around the 1000th unit. (It may be more or less, depending on the specific product being manufactured and the company’s production history.) Moreover, let us assume that our performance history allows us to assume our actual performance will be 2 times the standard at T-1000.

Exhibit 4 illustrates this concept. We can now draw a line from the T-1000 maturity point back to T-1 using the appropriate basic slope suggested by industry practice or empirical study. Assuming a standard value of 1,000 hours per unit, this yields a T-1000 estimate of 2,000 hours per unit. In our example, given a task of major aircraft assembly and assuming a basic slope of 80%, this yields a T-1 value of 18,480 hours per unit (2,000 hours per unit / 0.1082 unit factor at T-1000). This establishes the basic slope to which we can expect to recover over time.

Exhibit 4. Example of Applying Basic Slope and Realization



Our actual cost history at T-1 may be more or less than this value – in most cases, more. This is also illustrated in Exhibit 4. This is not surprising if we are experiencing a high degree of engineering and tooling changes and the supply chain has produced a significant number of part shortages. We expect that there will be improvements on the shop floor as engineering and the supply chain work to implement changes. But how fast will we recover, and to what value? The basic slope establishes what we can expect to recover to, as well as inform a decision about how quickly we can expect this to occur. As stated earlier, the crossover point can be expected between units 30 and 80 -- the exact point can be better established through research of prior programs. This can prevent a recovery slope that is unrealistically steep, resulting in overruns when the program is unable to perform, or slopes that are unrealistically flat, projecting bad performance too far into the future and inflating estimated prices. In short, the combination of the basic slope, the S-curve and industrial engineering standards can provide us a better estimate of future costs.

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Biography

Brent Johnstone is a production air vehicle cost estimator at Lockheed Martin Aeronautics Company in Fort Worth, Texas. He has 27 years' experience in the military aircraft industry, including 24 years as a cost estimator. He has worked on the F-16 program, and since 1997 has been the lead Production Operations cost estimator for the F-35 program. He has a Masters of Science from Texas A&M University and a Bachelor of Arts from the University of Texas at Austin.

