Trouble With the Curve: Engineering Changes and Manufacturing Learning Curves

Brent M. Johnstone

Lockheed Martin Aeronautics Company – Fort Worth

brent.m.johnstone@lmco.com

Trouble With the Curve: Engineering Changes and Their Impact on Manufacturing Learning Curves

Abstract (75-word limit): Engineering changes pose a dilemma for estimators: If learning curves assume cost improvement due to repetitive build, what happens when that repetition is interrupted by a change of task? Design changes are common occurrences, but rarely addressed in learning curve literature. This paper addresses how to analyze an engineering change by breaking it into its pieces and outlines techniques to calculate the reversionary impact on the learning curve to derive the estimated cost of change.

Key words: Learning Curves, Manufacturing, Engineering Changes, Methods, Modeling, Labor

Introduction

The learning curve demonstrates the cost benefit incurred by repetitively building a product over time. A cost curve "represents two facts: (1) that the time to do a job will decrease each time that job is repeated, and (2) that the amount of decrease will be less with each successive unit" (Fowlkes, 1963).

But what if the part design or the manufacturing process used to fabricate or assemble that part is altered? What if the job is no longer being repeated, but changes? What happens to everything that has been learned to date? A learning curve inherently assumes that the same task is being performed unit over unit – it is precisely that repetition of effort that is thought to create learning in the first place. So how do design changes impact the learning curve?

An engineering change will require the operator at a minimum to study and evaluate new planning to understand the change. He may need to review drawings and specifications for new engineering requirements. It may require him to learn new manufacturing methods or learn to use new or modified tooling. He may find himself in a new or altered work environment, accommodate new or changed production schedules, or submit to new or revised inspection criteria. (*Disruption*, n.d.) From an engineering or tooling perspective, changes may introduce errors in the design or tooling which may have to be subsequently fixed. The supply chain may have to start to produce new or revised parts which, if the engineering release is late, may create downstream part shortages on the assembly line. If we think of Anderlohr's five elements of learning (Anderlohr, 1969) – personnel, supervision, tooling, continuity of production, and methods -- we can see that any or all of these can be affected by an engineering change. All of this conspires to increase the number of hours to perform a changed task, at least initially.

The impact of an engineering change is best summarized by a General Dynamics training package from the early 1970s: Loss of learning "results from the re-introduction of problems associated with something new. These problems can vary widely and sometimes include tooling or engineering discrepancies. These discrepancies necessitate rework in fabrication or assembly areas. They contribute to the lost manhours or reduced efficiency. Therefore, they result in higher cost per completed end item from the point of reconfiguration." (*Learning Curves*, n.d.)

How then do we estimate this input? Surprisingly, most learning curve training packages make no reference to the manufacturing cost impacts of engineering changes. More commonly, they illustrate the cost impacts of production breaks. But engineering changes are far more common than a break in production. A long-running aircraft production program may experience as many as seven or eight major design changes before experiencing an actual production break if it ever does.

This paper reviews the ways we can assess and project these inputs.

Engineering Changes

In defense acquisition, engineering changes typically come in the form of an Engineering Change Proposal (ECP). We can think of engineering changes as doing one or more things:

1. A change may add tasks which did not previously exist.
2. A change may delete tasks which no longer must be performed.
3. A change may modify or reconfigure an existing task.

For discussion, Table 1. envisions a simple engineering change in a forward equipment bay of an aircraft which embodies all three cases.

Table 1. Example ECP with Notional Task Changes.

Additions:
* Add two (2) new antennas
* Add coax cables
* Add provisions (brackets, fittings)
* New access door
Reconfigured:
* Relocate existing systems
* Relocate existing harnesses and tubes
* Move bulkhead penetrations to accommodate changed provisions
Deletions:
* Remove one (1) existing antenna
* Remove related provisions

How would we evaluate the cost impacts of this change? We can separate the estimator's task into three categories:

1. Determine the baseline underlying learning curve prior to the change.
2. Isolate the portion of the total department task affected by the change. Identify the change to the affected cost centers and work breakdown structure. Relate this to the total department task.
3. Calculate the impact amount for the total.

We want to determine the expected hours per unit (HPU) impact of added, deleted, and reconfigured task prior to any consideration of possible learning loss or setback. The current value of deleted tasks is relatively easy – presumably we have cost history on what it takes us to perform these tasks today. For reconfigured task, we likely have current cost history on the existing part number but do not have history on the modified part. We will not have current history on added tasks – by definition, we are not performing those tasks today. But an estimate can be developed through a variety of methods – industrial engineering standards analysis, expert judgment, analogy to other parts on this or other programs using complexity factors, etc. In addition, a cost assessment could be performed parametrically by using a weight in/weight out analysis to calculate an hours per pound delta.

After the expected cost of the added, deleted, and reconfigured tasks is calculated, we next calculate the percent contribution each of these categories makes to the total component or subcomponent cost. In our example change, this ECP affects only part of a larger subcomponent, so there are areas which are not impacted. Table 2 provides a breakdown of HPU by estimating category.

Table 2. Sample ECP, Breakdown of Hours per Unit (HPU) by Category.

Last unit built (before change)		New part (after change, but w/o reversionary impacts)	
	HPU		HPU
Total (current design)	60	Unchanged task	42
		Reconfigured task	15
		Deleted task	(3)
		Added task	6
		Total (new design)	60

The left-hand side shows the current cost of the component (60 hours) before the change. The right-hand side shows the breakdown of the new part cost by category. Based on an industrial engineering analysis, we have concluded that 70% of the task, or 42 hours, will be untouched by the design change. Reconfigured tasks equate to 15 hours while the deleted task will remove 3 hours. Finally, the added task is estimated to be worth 6 hours.

The manufacturing cost of the new design (60 hours) is equal to the cost of the current design (60 hours). Can we conclude there is no delta cost impact for the engineering change?

We cannot because our analysis is incomplete. At no point have we accounted for the impact of reversionary impact on either the added or reconfigured tasks. *Every engineering change requires a consideration of reversionary impact on the learning curve.*

Reversionary Impact, Two Measurements

What do we mean by reversionary impact?

Reversionary impact is the unfavorable impact to cost that typically accompanies design changes. Reversionary impact, or loss of learning, is usually expressed in terms of setback on the learning curve. (Teplitz, 2014) To set back unit cost on a curve means to assume unit costs are based on cumulative unit positions earlier in the program. In other words, the program repeats a prior level of performance at a higher hours per unit cost.

Setback is typically calculated as follows:

Setback position = Break-in position x (1- Setback %)

Let us assume costs have been moving down an 85% unit learning slope. To date, 1,000 units have been built. To estimate the cost of the 1,001st unit, assuming a T-1 of 100 hours, we would calculate:

$(100 * 1{,}001^{-0.32193}) = (100 * 0.1979) = 20$ hours

Now instead assume a 50% setback occurs at the same 1,001st unit. The setback position – the new cost position incorporating the loss of learning – would equal:

1,000 x (1 – 50%) = 500.

(Note that the setback calculation is typically based on the cumulative number of completed units up to, but not including, the break-in point, since we are measuring how much cumulative learning to date will be lost.)

Because of the reversionary impact, we have lost an estimated 500 units of learning. That means when we estimate the cost for unit number 1,001, for learning curve purposes we estimate it on the learning curve *as if* it were unit number 501 -- that is, 500 units back up the learning curve. Then for our same curve:

$100 * 501^{-0.32193} = 100 * 0.2329 = 24$ hours

This 50% setback on the cost curve has resulted in a 20% increase in hours (from 20 hours per unit to 24 hours per unit).

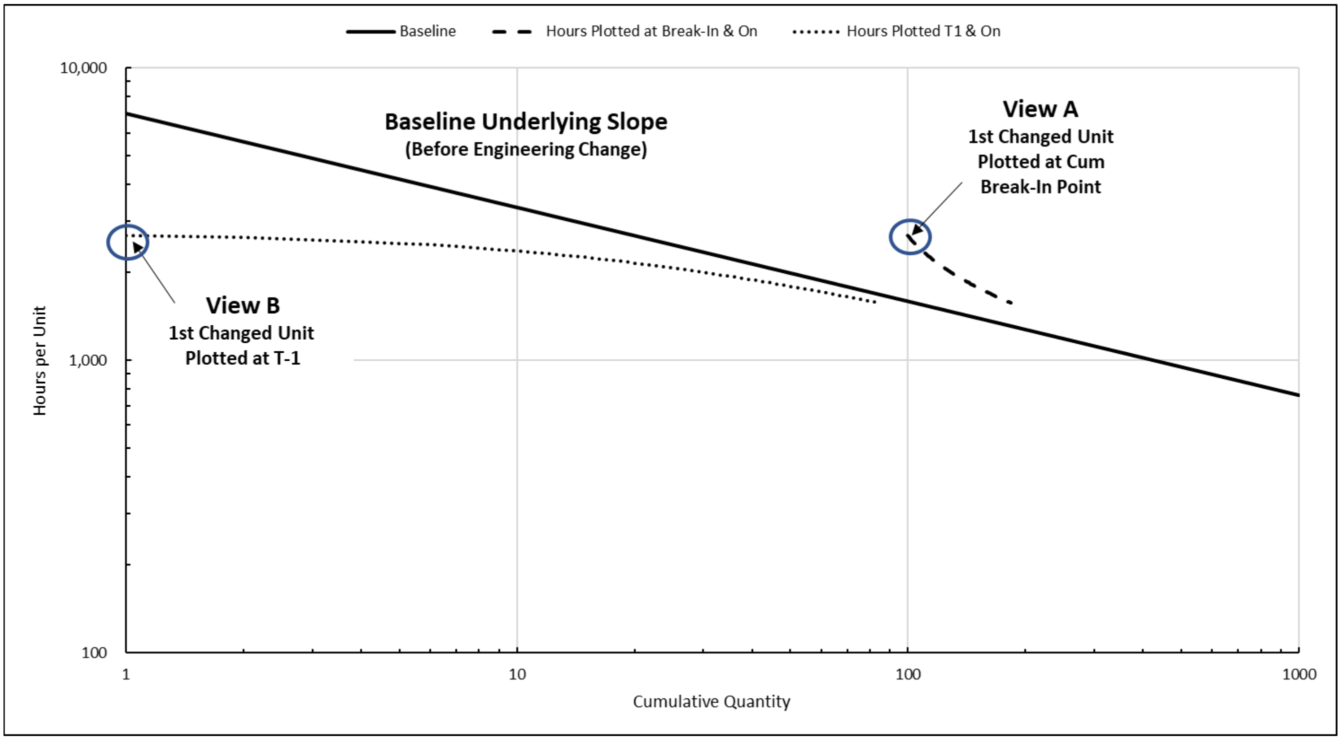
It's important to note that calculations of unit setback are *not* the same as calculations of learning loss as used in the Anderlohr production gap methodology (Anderlohr, 1968). A quick illustration will demonstrate the difference. Using the Anderlohr calculation of learning loss:

First unit cost	100 hours
Less T-1000 cost before setback	20 hours
Learned to date	80 hours
T-1001 cost before setback	20 hours
Less T-1001 cost after setback	24 hours
Hours of learning lost	(4) hours
Percent learning loss	5% (4 hours learning lost / 80 hours learned before setback)

Reversionary impacts can be viewed in terms of unit setback (50% in our example) or Anderlohr learning loss (5% in the same example). The Anderlohr learning loss factor will typically be less than the percentage of unit setback because of the logarithmic nature of the learning curve where most of the learning occurs in the front end of the learning curve, usually in the first 50 units. For our purposes in this paper, reversionary impact will be measured by percent setback on the learning curve.

Figure 1 shows two different ways to visualize reversionary impacts (Asher, 1956). Assume an engineering change that breaks at unit 100. In one case, the first changed unit is plotted at unit 100 and the subsequent units are plotted as unit 101, unit 102, etc. Call this View A. In the second case, the first changed unit is plotted at unit 1 and the subsequent units are plotted at unit 2, unit 3, and so forth. Call this View B. Essentially View B treats the first impacted unit as if it were a completely new aircraft at T-1.

Figure 1. Two Views of Reversionary Impact



Both views portray the same hours per unit data. But View A shows more vividly the connection between the experienced baseline curve (before the change) and the delta impact created by the change. This is less obvious in view B. As changes accumulate over time, View A provides an historical continuity which demonstrates the impacts of design changes as well as other programmatic impacts such as schedule or manpower changes. That is not easily done using the View B plotting methodology.

Setback: How Much Is Enough?

The next question for the estimator is: How far should we set back the added and reconfigured tasks?

The obvious answer is that these tasks should be set back all the way to T-1 again. University of San Diego professor Charles Teplitz is one learning curve writer who supports this approach, writing "that portion of the task that has been altered has, in essence, suffered a setback all the way back to unit 1." (Teplitz, 1991)

However, there is reason to believe this is an overly conservative view. It tacitly assumes that learning is primarily operator driven, where a task change and the associated loss of muscle memory would create a significant impact. However, Jefferson suggests the operator learning only contributes 22% to overall cost improvement, while tooling improvements (34%) and engineering changes to assist production (23%) are bigger contributors. (Jefferson, 1981) We noted earlier that an engineering change can impact any of Anderlohr's five elements of learning – personnel, supervision, tooling, continuity of production, and methods. But many engineering changes may affect only one or two elements, not all of them. For example, a small change -- the movement of a harness from one location to another in a bay – may require an operator to learn a new location to install the harness and its associated bracketry. But he need not relearn how to route a harness through a hole in structure, install clamps and studs properly, make connections, or perform electrical bond. Moreover, it may not affect tooling, create any part shortages, or require learning new manufacturing processes or methods. It is hard then to imagine that such a design change would push the cost of implementation of a reconfigured or even added task all the way back to the first unit cost. In the author's experience, a careful breakdown of historical cost deltas associated with engineering changes rarely shows a setback all the way back to T-1 for adds or reconfigurations.

So, if we need not return all the way to T-1, how far do we set back?

A careful examination of prior experience with design changes and correlating the observed cost setback against the nature of the change to the configuration allows us to construct tables for the estimator to use when determining how much setback to apply. Such a table would say large setbacks for highly invasive design changes and work its way down to smaller setbacks for relatively benign changes. Such reconfiguration can come from ECPs initiated earlier in the program, from a prior program at the same facility or data from other facilities. (*Manufacturing Direct Labor Change Impacts: Setback/Learning Gain*, n.d.*)* An example of a notional setback chart for an aircraft is shown in Table 3.

Table 3. Notional Setback Criteria.

X1% Setback (Highest) • New weapons system or design concept X2% Setback • Current weapons system but major revision to design, e.g., outer mold line change, total subsystem affected by change X3% Setback • Relocation of aircraft systems components with associated rerouting of provisioning (harnesses, cables, tubes, ducts) • Substantial wiring and tubing changes creating greater density and associated installation complexity • Material substitution within established manufacturing techniques X4% Setback • Moderate change in structure in part design details • Relocations of aircraft systems adjacent to original location • Lesser number of wires, tubes, ducts added X5% Setback • Limited change in structure with changes confined to hole patterns and locations, revisions in tolerances, etc. • Relatively small addition of wires, tubes, ducts X6% Setback (Lowest) • Minimal revisions in structural design • Very limited added wires, tubes, ducts

This table, while it relies on estimating judgment, is more defensible during a contract negotiation than relying on the analyst to simply pick a number out of the air. It will also force more consistent choices across the estimating team since each ECP will be analyzed using the same criteria.

This is important because, as we will see, the cost of a change depends significantly on the choice of a setback value. Table 4 shows the sensitivity of various setback decisions to the total cost. From a baseline T-1000 cost, we can see the cost impacts if we choose a 50% or 80% setback. We can also see that for the same setback value, the cost impact varies substantially if the learning curve slope is 80% or 90%:

Table 4. Setback Sensitivity Table.

		Slope = 80%		Slope = 90%	
Setback	Setback Unit	Unit Factor @ Setback	Increase from T1000	Unit Factor @ Setback	Increase from T1000
80%	200	0.1816	68%	0.4469	28%
50%	500	0.1352	25%	0.3888	11%
0%	1000	0.1082	0%	0.3499	0%

From the table, two things are apparent:

1. For a given learning curve slope, the higher the setback value, the larger the cost impact.
2. For a given setback percentage, the steeper the learning curve slope, the larger the cost impact.

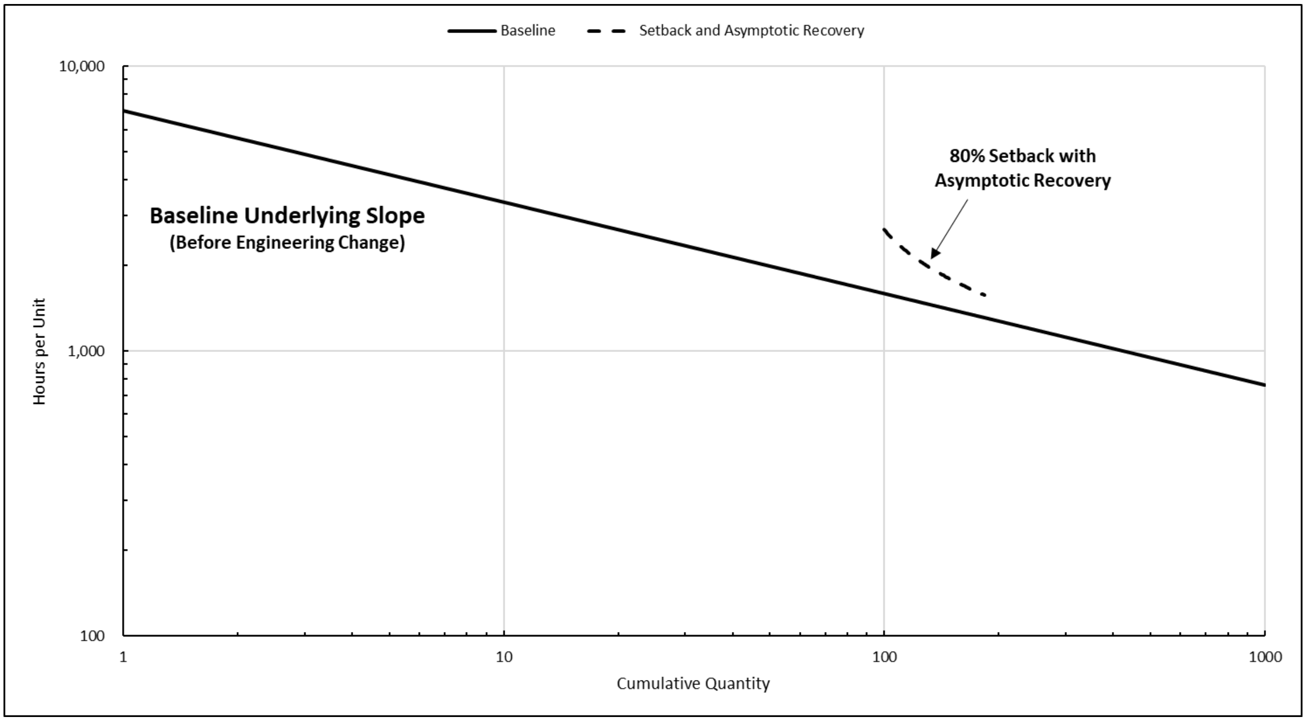
Recovery to the Baseline

Once we have established how back up the learning curve our unit costs are expected to return, the next question is: what happens from that point forward in time? As it turns out, there are two different approaches in the industry to how to deal with this.

The first method is the asymptotic recovery methodology illustrated by Figure 2. An engineering change breaks in at T-100 and cost returns to the equivalent point of T-20 on an 80% learning curve. We have lost eighty units of learning overall. The cost of the follow-on units (sequence numbers 101, 102, 103, 104, etc.) will be calculated using that same eighty-unit setback – that is, they will be calculated as if they were units 21, 22, 23, 24 and so on.

This brings the unit cost down relatively quickly. After 50 units after the design change is initiated, the unit cost is reduced 33% from the setback point. But the unit cost for the redesigned configuration will never reach the learning curve for the configuration before the change. Even at T-1000, the unit cost will be calculated as if the program was eighty units higher on the learning curve – that is, at T-920. The delta difference will be small, but it will still exist. Therefore, we say that the recovery is “asymptotic,” that the cost of the redesigned part will incrementally approach, but not actually equal, the baseline cost performance curve for the original design. The reversionary impact continues ad infinitum, although it eventually becomes so small that it cannot be distinguished on a normal logarithmic graphic.

Figure 2. Setback with Asymptotic Recovery.



The recovery is asymptotic because the redesigned part is assumed to come down the same learning curve slope as the original part design. How realistic is that assumption? Larry L. Smith comments: "[F]or most situations the items and units produced are similar and the work environment (company policy, management attitudes, etc.) is sufficiently stable that we expect the same rate of learning." However, Smith notes a learning curve slope change is appropriate if the ECP changes the manufacturing process from a manual process to a semi-automated or automated process. (Smith, 1976) Similarly, Teplitz writes: "Some changes affect the performance time or cost yet do not impact the slope of the learning curve. Others, on the other hand, could affect both requirement needs and learning curve slope." (Teplitz, 1991) Such a change in manufacturing process is not typical of most ECPs, however. Such changes usually require large tooling and facility non-recurring costs that most customers are unwilling to pay unless there is an immediate, near-term payback in cost savings.

A Different Approach

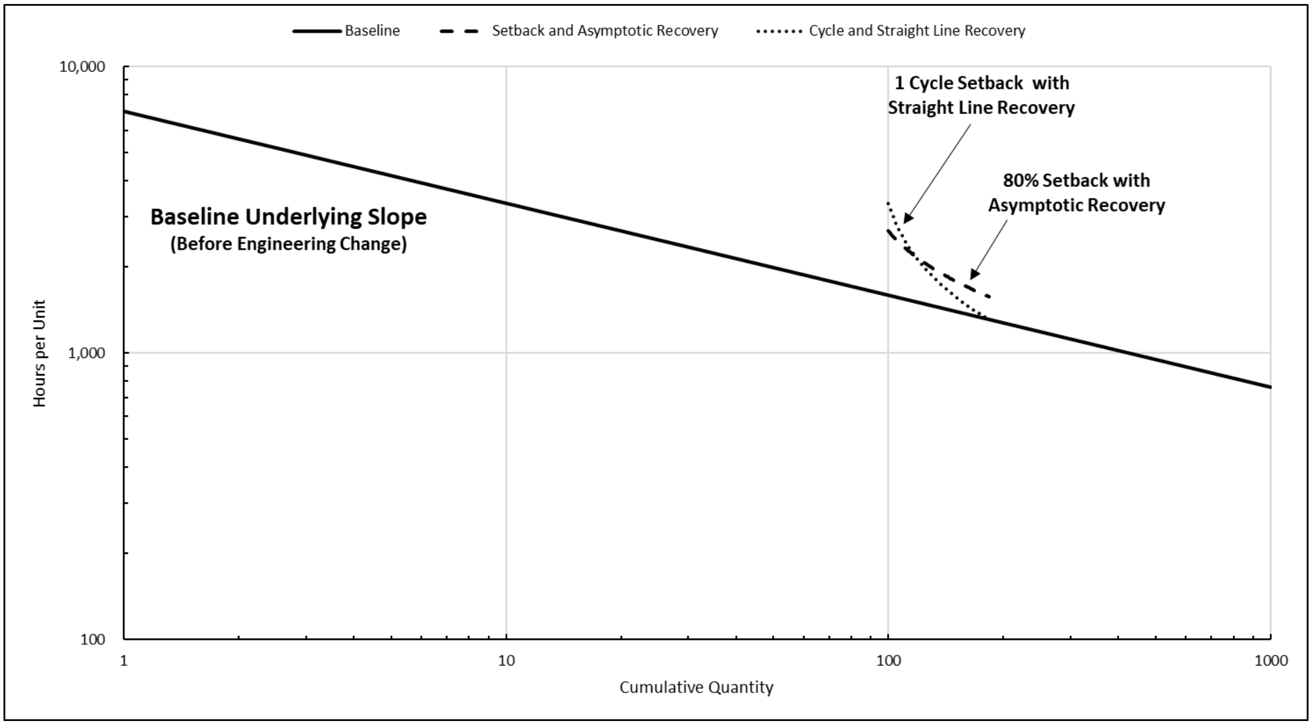
The method the author has described – which we will describe as the "Variable Setback with Asymptotic Recovery" methodology -- is probably the most common industry approach for dealing with design changes. But it is by no means the only one. We'll contrast our first example with a second approach.

Instead of varying the unit setback depending how extensive the design change is, we could employ a universal rule of thumb applicable in all cases to how much setback is applied. One method is to employ a "one cycle" setback. Tracing back no doubt to the days of hand plotted charts on special paper pre-printed with logarithmic scales -- not so long ago in the author's career! -- this method moves the position on the cost curve back one logarithmic cycle from the break-in point. For example, if 700 units have been built at the time of the change, the setback is calculated as unit 70 (700 divided by 10). If

1,000 units have been built, the setback is calculated at unit 100 (1,000 divided by 10). A very extensive design change set back two cycles (from unit 700 to unit 7, or 700 divided by 100).

This one cycle setback methodology is paired with a different approach of recovery to the baseline. In this methodology, cost returns on a straight-line projection to the underlying baseline curve with intersection at some predetermined number of units. Unlike the asymptotic recovery, the manufacturing performance after the change returns to the pre-change cost curve at some point and continues as if the change had never occurred. The reversionary impact goes to zero. This can be seen in Figure 3.

Figure 3. One Cycle Setback with Straight Line Recovery.



This method also allows for the reversionary impact to be adjusted for the extent of the design change. However, instead of calibrating the amount of setback, the number of recovery units is calibrated to a higher number of units for significant design changes and a smaller number of units for more benign design changes. An extensive change may take 200 units to recover to the baseline, while a smaller change might only take 40 units.

What are the advantages and disadvantages of these approaches? The one cycle setback rule – equivalent to a 90% unit setback applied in all cases -- seems appropriate in some cases, less so for smaller design changes. That may be a more difficult “sell” during contract negotiations. A small design change would of course show a quick recovery over a short build run. Paired together, this may produce a shockingly steep effective learning curve that might be equally difficult to sell to the production managers responsible for carrying out the effort.

On the other hand, the asymptotic recovery approach is somewhat more difficult computationally than calculating a straight-line recovery. In addition, as the post-change hours per unit approach those on the baseline curve, there may come a point where the delta is so close it becomes immaterial. How long must we continue to carry it? The straight-line approach eliminates that concern.

More consequentially, the asymptotic recovery is usually underpinned by an assumption that the post-change learning curve slope will be the same as the slope before the change. But what if the learning curve slope is steeper? Then the post-change slope will intercept the pre-change cost curve, producing an answer like the straight-line approach.

There may be cases where such an accelerated recovery curve is desired. Cochran (1968) suggests a formula that is easily incorporated into the conventional recovery curve. He suggests use of a multiplier k_n for to be used for a n_0 amount of setback:

$$k_n = \frac{d}{d + (n - n_1)}$$

where n_1 represents cumulative units before break-in and n_0 or $(n\text{-}n_1)$ represents the units of setback. The estimator chooses a value d as an accelerant for the recovery curve. Through experience, Cochran determined the optimal values of d are between 20 and 50. The smaller the value of d, the faster the recovery will be.

As an example, imagine an 85% baseline slope with a 50-unit setback for a design change implemented at unit 100 and an assumed d factor of 20. Table 5 shows the associated calculations. At unit 100, the units of setback are the same – 50 units – in the normal and accelerated recovery cases. However, at unit 150 the accelerated recovery curve only sets back 14 units, such that:

$$k_{150} = \frac{20}{20 + (150 - 100)} = 0.286$$

We can use this to calculate the adjusted units of setback at T-150 as follows:

$$k_{150}\ x\ n_0 = \ 0.286\ x\ (150 - 100) = 14$$

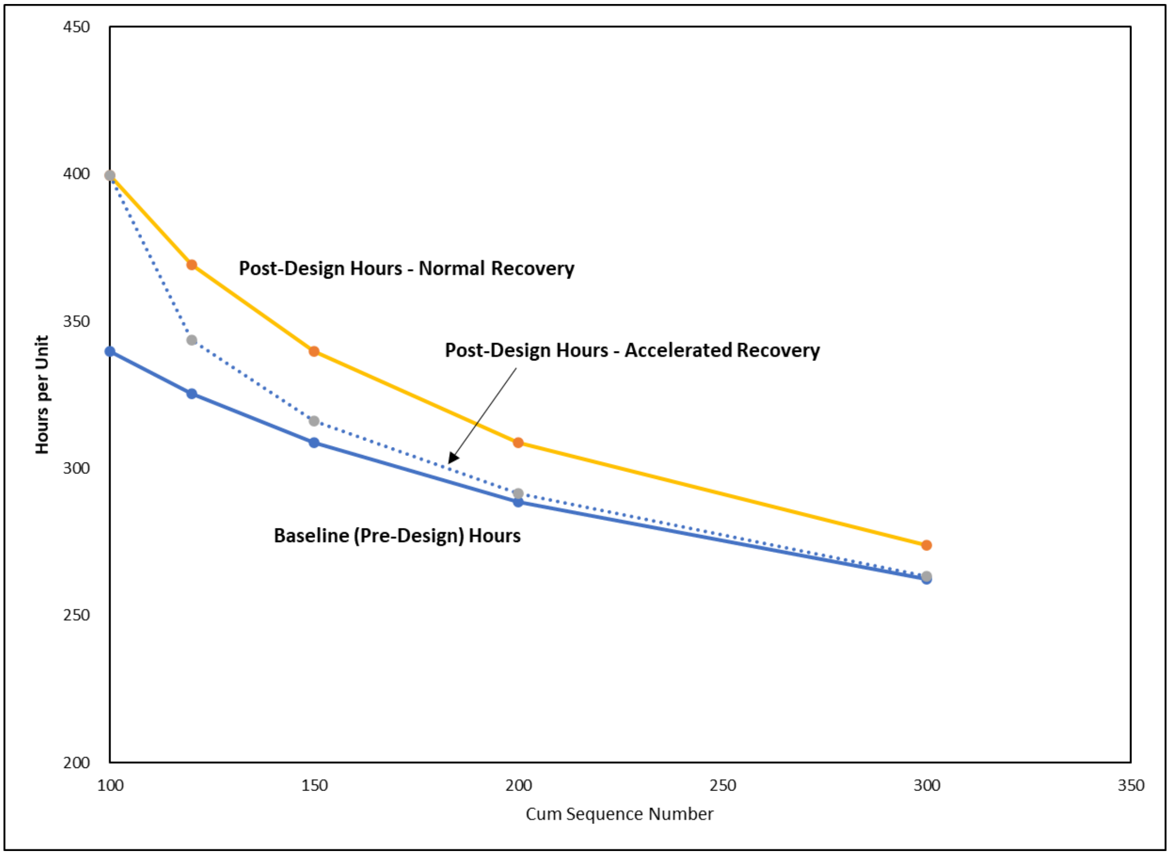
Consequently, instead of estimating an HPU of 340 hours at T-50 as the normal recovery curve would yield, an accelerated recovery curve would estimate an HPU of 316 hours (versus 309 HPU for the pre-change learning curve).

Table 5. Example of an Accelerated Recovery Curve

Slope	85%	d =	20 units			k = d / [d + (n - n_1)]					
Beta	-0.23447	n_1 =	100 units cum experience before break-in unit								
TFU	1000										
Base Calculation		50 Unit Setback - Normal Recovery				50 Unit Setback - Accelerated Recovery					
Unit	HPU	Setback	Unit	HPU	Delta	k	Setback	Unit	HPU	Delta	
100	340	-50	50	400	18%	1.00	-50	50	400	18%	
120	325	-50	70	369	13%	0.50	-25	95	344	6%	
150	309	-50	100	340	10%	0.29	-14	136	316	2%	
200	289	-50	150	309	7%	0.17	-8	192	292	1%	
300	263	-50	250	274	4%	0.09	-5	295	263	0%	

Figure 4 shows graphically the two different recovery slopes. In the first case, a normal asymptotic recovery is plotted. In the second, an accelerated recovery is plotted. Assuming a k factor of 20, the accelerated recovery HPU equals the baseline HPU by T-300 after 200 units have been built, where the normal asymptotic recovery curve is still 4% higher than the baseline at the same point.

Figure 4. Accelerated Recovery Curve



Sample ECP – Calculations of the Cost Delta

Let us return to our original example – an ECP affecting the forward equipment bay of an aircraft. How might we apply these concepts to calculate the reversionary impact and the final cost impact?

In our example, we will apply the variable setback with asymptotic recovery methodology. We will apply a notional 75% setback since this change involves the relocation of aircraft systems components with rerouting of the associated provisioning.

Table 6 shows the parameters associated with our notional ECP.

Table 6. Notional ECP Parameters.

* Last unit built	200
* HPU at last unit built	60
* Assumed slope	80%
* Theoretical first unit (TFU)	330
* Setback	75%
* Equivalent last built	50

		HPU at Break
Added Task	10%	6.0
Reconfigured Task	25%	15.0
Deleted Task	-5%	(3.0)
No Change	70%	42.0
Total	100%	60.0

Table 7 calculates the baseline estimate for the task had no design change taken place. We will carry out the estimate for the next 300 units after the change, which breaks in at T-201. The cumulative factor difference (CFD) shown in the table is the sum of the individual learning curve unit factors over the range of aircraft in the lot, such that T-1 hours x CFD equals the total estimated lot hours, i.e., 330 T-1 hours x 8.7459 Lot 10 CFD = 2,889 Lot 10 hours.

Table 7. Baseline Estimate.

Baseline Slope (no Engineering Change)

Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	201	250	225	50	8.7459	2,889	58
11	251	300	275	50	8.1975	2,708	54
12	301	350	325	50	7.7677	2,566	51
13	351	400	375	50	7.4177	2,450	49
14	401	450	425	50	7.1246	2,353	47
15	451	500	475	50	6.8739	2,271	45
				300	46.1273	15,236	51

Table 8 shows the estimate for the added task. Notice that we have applied a 75% setback, beginning our calculations at T-51 on the learning curve.

Table 8. Added Task – Debit Estimate.

Added Task - Debit

Added Task Hours Before Setback	6.0		
Unit Factor at Break-In	0.1816		
Added Task TFU	33.0	10%	of total TFU

Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	51	100	73	50	12.5291	414	8
11	101	150	124	50	10.5827	350	7
12	151	200	174	50	9.4864	313	6
13	201	250	225	50	8.7459	289	6
14	251	300	275	50	8.1975	271	5
15	301	350	325	50	7.7677	257	5
				300	57.3093	1,893	6

Tables 9 and 10 show our estimate for the reconfigured task. We will calculate this in two steps. First, we will credit the reconfigured task without setback as shown in Table 9. Second, we will debit the reconfigured task with setback as shown in Table 10. The delta of course is the reversionary impact.

Table 9. Reconfigured Task – Credit Estimate.

Reconfigured Task - Credit

Reconfigured Task Hours Before Setback	(15.0)		
Unit Factor at Break-In	0.1816		
Reconfigured Task TFU	(82.6)	-25%	of total TFU

Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	201	250	225	50	8.7459	(722)	(14)
11	251	300	275	50	8.1975	(677)	(14)
12	301	350	325	50	7.7677	(641)	(13)
13	351	400	375	50	7.4177	(613)	(12)
14	401	450	425	50	7.1246	(588)	(12)
15	451	500	475	50	6.8739	(568)	(11)
				300	46.1273	(3,809)	(13)

Table 10. Reconfigured Task – Debit Estimate.

Reconfigured Task - Debit

Reconfigured Task Hours Before Setback				15.0			
Unit Factor at Break-In				0.1816			
Reconfigured Task TFU				82.6	25% of total TFU		
Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	51	100	73	50	12.5291	1,035	21
11	101	150	124	50	10.5827	874	17
12	151	200	174	50	9.4864	783	16
13	201	250	225	50	8.7459	722	14
14	251	300	275	50	8.1975	677	14
15	301	350	325	50	7.7677	641	13
				300	57.3093	4,732	16
		Delta Hours for Reconfigured Tasks				923	3

Finally, we will calculate a credit for the deleted task as shown in Table 11. We have not applied any setback since the design change has eliminated this effort.

Table 11. Deleted Task – Credit Estimate

Deleted Task - Credit

Deleted Task Hours Before Setback				(3.0)			
Unit Factor at Break-In				0.1816			
Deleted Task TFU				(16.5)	-5% of total TFU		
Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	201	250	225	50	8.7459	(144)	(3)
11	251	300	275	50	8.1975	(135)	(3)
12	301	350	325	50	7.7677	(128)	(3)
13	351	400	375	50	7.4177	(123)	(2)
14	401	450	425	50	7.1246	(118)	(2)
15	451	500	475	50	6.8739	(114)	(2)
				300	46.1273	(762)	(3)

Finally, we will take the totals of Tables 7 through 11 to show the sum of the added, deleted, and reconfigured tasks.

Our baseline is our method of manufacture and associated cost before the change is implemented. Mathematically, then:

- Debit = Hours for added and reconfigured tasks including reversionary impacts.
- Credit = Hours for any tasks eliminated by the change.
- Cost of change = Debit – Credit hours.

In total, the design change produces an additional 2,055 hours over the baseline. Over the course of the 300 units, the redesigned subcomponent will take 58 hours per unit (versus 51 hours per unit) or an increase of 13.5%.

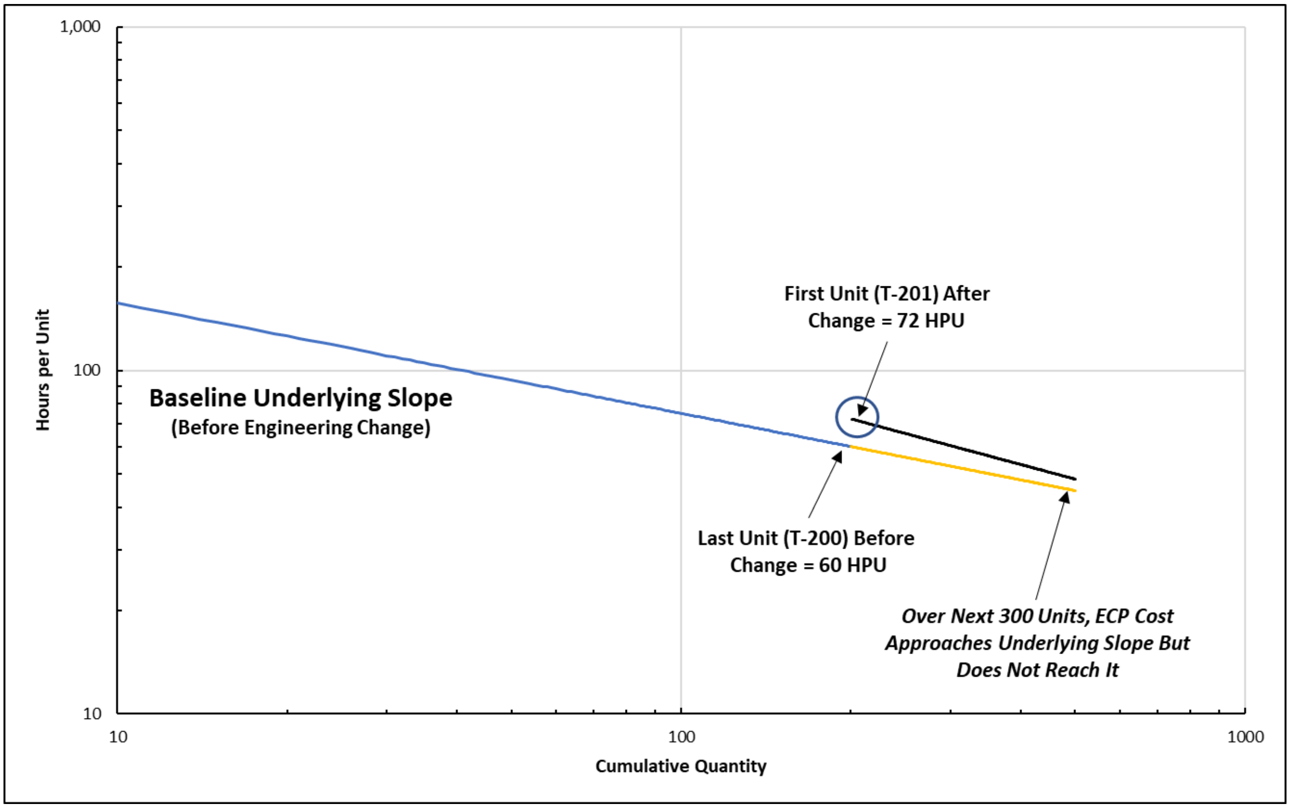
Table 12. Sum of Added, Deleted and Reconfigured Tasks.

Sum of the Totals								
Lot	Baseline	Credit Reconfig	Debit Reconfig	Debit Added	Credit Deleted	Total Hours	HPU	% Delta
10	2,889	(722)	1,035	414	(144)	3,471	69	20.1%
11	2,708	(677)	874	350	(135)	3,119	62	15.2%
12	2,566	(641)	783	313	(128)	2,893	58	12.7%
13	2,450	(613)	722	289	(123)	2,726	55	11.3%
14	2,353	(588)	677	271	(118)	2,595	52	10.3%
15	2,271	(568)	641	257	(114)	2,487	50	9.6%
	15,236	(3,809)	4,732	1,893	(762)	17,291	58	13.5%

Baseline Hours (Lots 10-15)		15,236
Debits:		
Added Task	1,893	
Reconfigured Task Delta	923	
Credits:		
Deleted Task	(762)	
Total Cost of Change	2,055	
ECP Hours (Lots 10-15)		17,291

A plot of the resulting hours is provided in Figure 5. Notice that the “scallop” pattern seen in the earlier graphs of the post-change curve is not as pronounced. That is because in this example 70% of the subcomponent build is unaffected by the ECP. This has the effect of dampening the initial “bump” in the post-change hours per unit.

Figure 5. Notional ECP Hours per Unit, Before and After Change



Conclusions

The Greek philosopher Heraclitus said, "Everything changes, and nothing stands still." Change on the manufacturing shop floor is a disrupter. It forces reevaluation of production schedules, tooling and plant layouts, crew tasks and responsibilities – and cost. Long cycle products like aircraft, missiles, and spacecraft – all of whom share lengthy production schedules, complex designs and demanding customers -- are particularly impacted by these engineering changes.

Estimating the impact of engineering change proposals can be challenging for the cost estimator. It requires not only an understanding of the current shop conditions and the associated cost, but a careful breakdown of the tasks to be added or reconfigured by the ECP. Assistance from the design engineering, manufacturing engineering, and tooling functions can be invaluable in making these determinations. Lastly, the recognition that learning can be lost and regained over time, paired with a consistent and logical breakdown of the problem, can assist the analyst in making fair and reasonable cost estimates.

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Biography

Brent Johnstone is a Lockheed Martin Fellow and production air vehicle cost estimator at Lockheed Martin Aeronautics Company in Fort Worth, Texas. He has 35 years' experience in the military aircraft industry, including 32 years as a cost estimator. He has worked on the F-16 program and has been most recently the lead Production Operations cost estimator for the F-35 program. He has a Master of Science from Texas A&M University and a Bachelor of Arts from the University of Texas at Austin.