Funding—A Unified Approach

Tom Warwick*
Pratt & Whitney, United Technologies Corporation, West Palm Beach, Florida 33410

Trend and trade funding relationships are presented to reduce cost and to quantify cost breakevens as well as paybacks and allocations. The relationships can be applied to the "Big 3" life cycle cost (LCC) elements: research and development, acquisition, and operating and support. The approach is a new application of the improvement curve and increases the usefulness of the improvement curve from trend only. The approach provides the capability to trend and trade driven and total cost with driver cost, funding. The approach is unified because its funding relationships are fundamental relationships that can be applied to each of the LCC elements and their subelements, separately or sometimes together.

Nomenclature†

A = proportionality constant
B = trend curve exponent; instantaneous percent slope; improvement curve log-slope
C = prevailing cost payback; trend curve instantaneous slope
dT/dX = trade curve instantaneous slope
dY/dX = trend curve instantaneous slope; prevailing cost payback
L = learning, %
T = total cost; driver and driven cost
T_M = total cost at a minimum total cost
T_{PC} = total cost at a prevailing cost payback
X = driver cost; funding
X_M = driver cost for minimum total cost
X_{PC} = driver cost for a prevailing cost payback
Y = driven cost; cost other than driver cost
Y_M = driven cost at minimum total cost
Y_{PC} = driven cost at a prevailing cost payback
Y/X = cost ratio of driven and driver cost

Introduction

THE unified approach of this paper brings together trade curve methodology used by life cycle cost (LCC) analysts and improvement curve and trend curve methodology used by development, manufacturing, and reliability engineers. The methodology presented is applicable to most systems including propulsion/aircraft systems. This paper is a sequel to an earlier paper.[1]

Funding and cost discussions are complicated because of inadequate information. Even with prior experience, the cost benefit tomorrow derived from funding more or less today is a matter of speculation. Different levels of authority with divergent agenda can have executives (with the people they manage) lacking in knowledge about funding decisions or cost consequences. Deficient and inefficient suboptimization of cost allocation and reduction is an unwanted result.

What is Needed

Funding relationships are needed for cost allocation and reduction of the "Big 3" major LCC elements and their subelements, separately and sometimes together. A quick and easy way to use common analysis for improvement, a unified approach, is needed to link together the different analyses of development, manufacturing, reliability, and life cycle cost.

Explicit relationships to directly link trend and trade cost are needed to provide better means to quantitatively answer funding and cost questions. What is too much? Too little? Just enough? Where's the knee in the curve?

What is Presented

Because funding and cost are sensitive proprietary issues, actual or projected information for specific programs, products, or processes are not revealed. Explicit trend and trade funding relationships to reduce cost and to quantify cost breakevens, as well as paybacks and allocations, are presented. A numerical trend and trade example to enhance understanding also is presented.

Cost and Funding Concerns

Culmination points, cost breakevens where with additional funding more is lost than gained, are cost and funding concerns. Will the improvement curve go flat now or later? Should it? Why? Where's the knee in the curve?

While improvement-curve information content needed to answer these and other questions is nearly complete, answers to these questions are not apparent with existing applications of the improvement curve; e.g., Wright, Crawford, Duane, and Doll[2–8] (WCDD) improvement curves.

Improvement Curve

The improvement curve is well known by its log-log characteristics and its many applications. Its many descriptive terms used for identification also are well known and include learning curve, growth curve, cost reduction curve, progress curve, and experience curve.

This paper uses the descriptive term "improvement curve" for the log-log plot (Figs. 1–4). For convenience and discussion ease, the descriptive term "trend curve" is used for the arithmetic plot (Fig. 5). In this paper, the improvement curve and the trend curve are synonymous except for their log-log and arithmetic forms of presentation.

A chronology of improvement curve and trend curve use for the three major LCC phases starts with the acquisition phase application, since the curve first was used for that phase.

Acquisition

The improvement curve is used to monitor and predict cost and price with quantity. As early as 1922, Wright, a manufac-

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*Manager, System Cost and Value Engineering. Associate Fellow AIAA.

†The sign convention used for the trend curve exponent B is such that B itself is positive, see Eq. (1). For convenience and discussion ease, funding is uniquely defined and used synonymously with driver cost. Subscripts purposely have been kept simple to allow nearly a 1:1 correspondence of nomenclature with computer code.

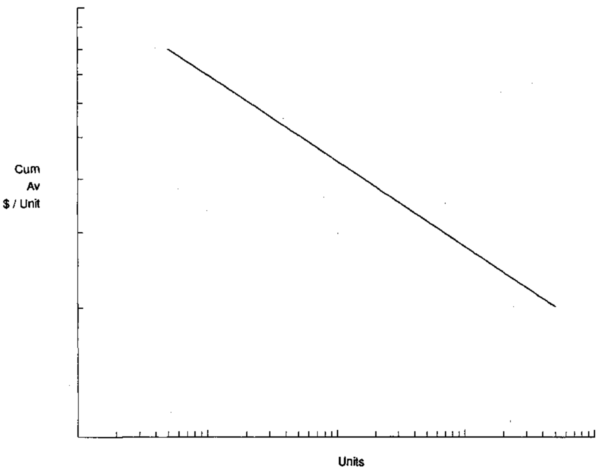

Fig. 1 Wright curve.

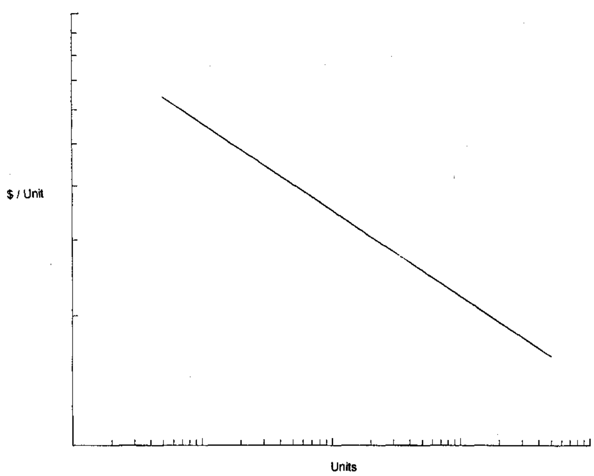

Fig. 2 Crawford curve.

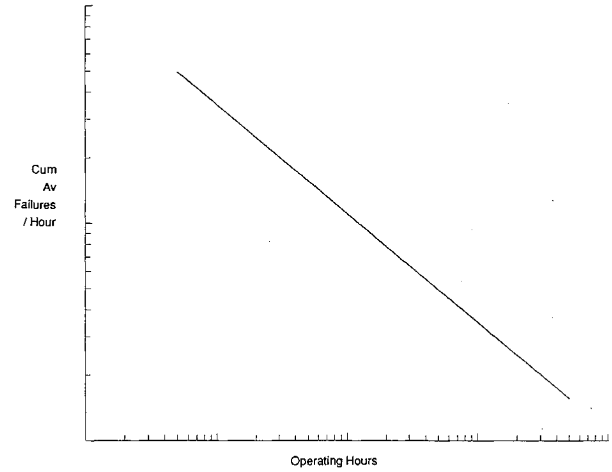

Fig. 3 Duane curve.

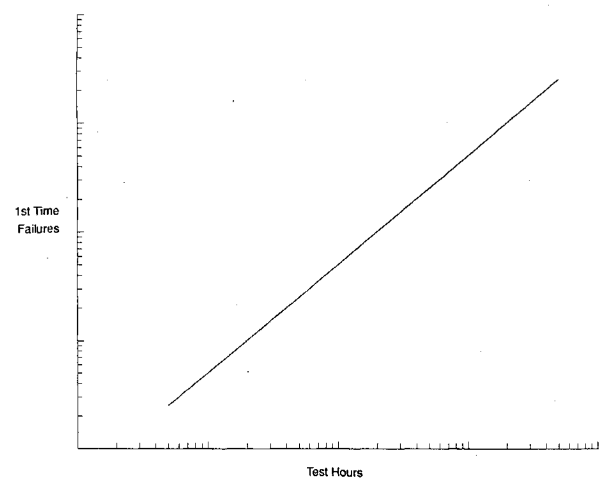

Fig. 4 Doll curve.

turing engineer, and others conducted relationship studies of the variation of cost and price with quantity produced. In 1936, Wright[2] presented the relationship of cumulative average unit cost with quantity, the Wright curve (Fig. 1).

During World War II, Crawford[3] produced a report that presented his relationship studies of unit cost with quantity, the Crawford curve (Fig. 2). About 20 years later, some fully accepted the improvement curve even though its "constant" log-slope could vary and also might be somewhat flat at the very beginning and end of the curve (Cochran's inverted S curve). Cochran's observation regarding the improvement curve log-slope B is pertinent here: "When deviation from this pattern (improvement curve log-slope) occurs, it can usually be related to specific causes. A wide variety of slopes is met within actual practice, with values of 50–95% not uncommon. But slopes from 80 to 95% are the most fundamental and long lasting."[4]

Others did not accept the improvement curve. Managements failed to recognize technological progress is a kind of learning. For example, production of the Ford Model T started in 1909. From 1910 (and 12,000 cars) to 1926 (and 15,000,000 cars), price reduction in constant year dollars had an improvement curve "slope of about 86%" ($B = 0.217$).[5]

Operating and Support

The improvement curve is used to monitor and predict reliability. In 1964, Duane,[6] a reliability engineer, presented his relationship studies of failure rate with operating hours, the Duane curve (Fig. 3). He focused on effect and on decreasing failure rate as first time failures are corrected and eliminated (the downstream portion of the failure rate improvement process).

Research and Development

The improvement curve is used to monitor and predict engine development and cost. In the 1970s, Doll, a development engineer, wrote reports that, in addition to documenting reseach and development (R&D) engine costs,[7] developed "problem finding tracking curves,"[8] first occurrence at test and in the field of new failure modes. He presented a relationship of first time failures with test hours, the Doll curve (Fig. 4).

Doll focused on cause and on high yield testing to find first time failures earlier, the upstream portion of the failure rate improvement process. For high yield development testing, a unity Doll improvement curve log-slope and steeper has been repeatedly documented. Similar results of learning better than 50% ($B = 1.0$, $\%Y/\%X = 1.0$) have been reported for R&D program activity; i.e., the percent change of program performance with R&D funding is more than $1:1$.[9]

Doll and Duane curves are related by cause and effect, or the find and correct reliability improvement process. The Duane improvement curve has a straight line decreasing log-slope. The Doll curve is an inverse improvement curve because it has a straight line increasing log-slope. About a decade prior to Doll, some already had accepted the improvement curve reliability growth model for service and test use.[10] For brevity, more specific details of the inverse improvement curve are not addressed by this paper. This paper is focused on the decreasing improvement curve.

Cost Cause and Effect and Closure

Wright, Crawford, Duane, and Doll did not consider funding as a cost driver or total cost as a closure mechanism, and they incompletely considered cost cause and effect, driver cost and driven cost.

The cost-related relationships studied by Wright and Crawford for the acquisition phase and by Doll and Duane for the R&D and operating and support (O&S) phases are based on the improvement curve. But the cost-related driver considered by Wright and Crawford was quantity, units, and the cost-related driver considerd by Doll and Duane was hours, test and operating hours.

The contributions of all four men are substantial. Using WCDD improvement curves, cost with cost-related parameters such as units and hours can be calculated and trended. But cost closure is missing. Something more is needed—a unified approach—to trend and trade cost.

Two Enduring Challenges

Nomenclature is an enduring challenge because sometimes the same thing has different meanings. The situation is like an American and an Englishman who mistakenly believe they speak the same language when in fact they do not. A paucity of cost data and estimates is another enduring challenge. Somehow we never have enough.

Nomenclature

More tolerance and understanding are needed to comprehend what is being communicated. Cost and price are an example of a nomenclature challenge. Cost to a customer is price to a supplier. Total cost is another example. Total cost is more than just an industry or government acquisition cost. It is more than just a supplier R&D cost or customer O&S cost. Total cost is defined equal to the total sum of the "Big 3" life cycle costs for a program, product, or process.

This definition of total cost is used by the government and means "the sum of development, production, operating and support costs."[11] A total cost less than that defined here can result in deficient and inefficient suboptimizations, "worse than a thief" results with best value not achieved. That is, a thief steals resources generally causing a reallocation of those resources with little if any waste. Suboptimization of total cost wastes resources and is "worse than a thief."

As previously noted, funding is uniquely defined and used synonymously with driver cost. For additional clarification, a statement using driver cost, driven cost, and total cost follows. Funding (driver cost) is a cause to effect driven cost and achieve a total cost reduction. The driver, driven, and total cost nomenclature used here is compliant with government requirements to "ensure coherence among cost and engineering documentation."[12]

Cost Data and Estimates

Improvement curve data sources and projection estimates are another enduring challenge. "Accounting methods seldom reveal such data."[2] How a paucity of cost data and estimates can be obviated is addressed in the following section, which describes the unified approach.

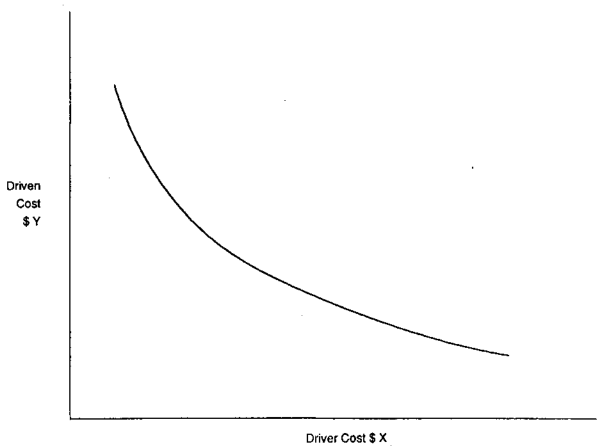

Fig. 5 Typical trend curve.

Unified Approach

The unified approach is applied to calculate funding and allocate and reduce cost. The unified approach relates cause, funding (driver cost), with effect, driven cost. The unified approach trends driven cost with driver cost and emphasizes total cost by trading total cost with driver cost.

Cost Units

To facilitate the unified approach, both driver cost and driven cost are required to be quantified in the same cost units. Ordinate (Y) and abscissa (X) need to be expressed in the same cost units, that is, the same cost units are required for the approach to be unified. Having the same cost units provides analysts and managers with an improvement curve cost calculating and estimating capability 1) to trend and trade driven and total cost with driver cost and 2) to allocate driver cost and reduce driven and total cost.

The unified approach requires that driver cost and driven cost be directly comparable in the same cost units such as constant-year dollars (U.S.). For simplicity of the approach, discounted and then-year dollars are not recommended.

Later cost, such as O&S, generally is underestimated more than earlier cost, such as R&D and acquisition. Adjustment of the underestimated later cost is recommended for a more realistic, reasonable, and complete LCC. Considering this adjustment and discounting to be a "wash," constant-year dollars are recommended.

To account for the time value of money, the author prefers the above approach. If the underestimated later cost adjustment is not a wash with discounting, the author suggests the use of constant-year dollars accompanied by an appropriate adjustment to prevailing cost payback. Some loss of model fidelity and calculation accuracy can occur but is acceptable for many analyses.

Adjusting prevailing cost payback, if required, and following this suggestion, funding then is calculated "the same way" with constant-year dollars whether or not the time value of money is significant. Calculating funding the same way in constant-year dollars does not necessarily result in the same calculated funding level. The calculated funding level is dependent on the adjusted value of the desired prevailing cost payback.

Trend Curve

As previously discussed, the improvement curve log-log plot when presented as an arithmetic curve X-Y plot is called a trend curve (Fig. 5). The trend curve describes driven cost Y with driver cost X.

Unlike the constant log-slope B of the decreasing improvement curve (Figs. 1–3), the decreasing trend curve instantaneous slope C, prevailing cost payback, is not constant; it is a continuously diminishing slope (Fig. 5). Both log-log and arithmetic plots reflect a situation of a constant percent reduction $[B = -(\%Y)/(\%X)]$.

The author cautions the reader that paybacks claimed by some are frequently average cost payback ($\Delta Y/\Delta X$) and not prevailing cost payback ($\mathrm{d}Y/\mathrm{d}X$). Similarly, the reader also is cautioned that the cost ratio of driven and driver cost (Y/X) sometimes is quoted as payback. For this paper, payback is defined as prevailing cost payback ($C = -\mathrm{d}Y/\mathrm{d}X$).

Trade Curve

The trade curve describes total cost T with driver cost X. Both driver and driven costs are in the same cost units and are directly summed. Total cost T is the sum of driver cost X and driven cost Y.

For better comprehension and application of the unified approach, Cartesian X-Y arithmetic coordinates are recommended and are used for both the trend curve and the trade curve (Figs. 5, 6).

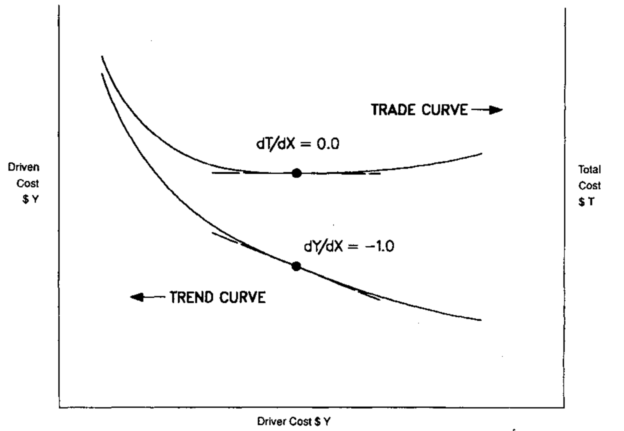

Fig. 6 Typical trend curve with trade curve.

Where is the knee in the curve? The answer is at or before breakeven. At the trend curve breakeven 1 : 1 culmination point, the trend curve instantaneous slope is unity, $(dY/dX) = -1.0$, and the trade curve instantaneous slope is zero, $(dT/dX) = 0.0$ (Fig. 6).

Before breakeven, prevailing cost payback C is greater than 1.0; that is, for every dollar funded more than a dollar is saved. After breakeven, prevailing cost payback C is less than 1.0; that is, for every dollar funded less than a dollar is saved.

Two or More Points Known

Two points are required to be known to calculate the two parameters of the trend curve: the proportionality constant A and the trend curve exponent B. If only two points (X_1,Y_1) and (X_2,Y_2) are known, the trend curve exponent B is directly calculated by Eq. (6), presented in a following section of this paper. Once the trend curve exponent B is calculated, the proportionality constant A is calculated with Eq. (1) by using B and one of the known two points (X-Y). Equation (1) also is presented in a following section of this paper.

If more than two points are known, a fitted first-order equation—a least squares straight line for the log-log improvement curve—can be calculated. The technique can be accomplished on many hand-held calculators. The intercept of the straight line is the log of the proportionality constant A. The slope of the straight line is the improvement curve log-slope B.

In government aircraft gas turbine engine programs, documented and approved sources for two or more known points are available; e.g. Component Improvement Program (CIP). Funding for CIP and its claimed net total cost savings are a matter of record. Other government and contractor programs also have documented and approved sources for two or more points; e.g., government and contractor sponsored value engineering (VE). Funding for VE and claimed contract net total cost savings are a matter of record.

One Point Known

"To use it [improvement curve], you have to know what the proper starting figures are and what percent reduction to use."[13] That is, if the trend curve exponent B is known, which also is the instantaneous percent slope and the improvement curve log-slope, only one point is required to be known, a "starter" point (X-Y). Using the starter point (X-Y) with the trend curve exponent B and Eq. (1), the proportionality constant A can be calculated. As previously stated, Eq. (1) is presented in a following section of this paper.

Alternatively, if only the starter point is known, the trend curve exponent B needs to be assumed. The improvement curve procedure for this case is similar to the procedure Weibull reliability analysts use when the Weibull exponent beta is not known. This procedure, assuming the trend curve exponent B, uses past experience. A representative B is available for selection from many texts.[4,14] Alternatively, knowing the "Big 3" life cycle phases appropriate for the specific situation, a representative B can be selected by considering separately and sometimes together WCDD curves and similar improvement curves for the program, product, or process of interest. Once the trend curve exponent B is assumed, the trend curve exponent A is calculated using Eq. (1) as previously described.

No Points Known

What is needed is a starter X-Y point and the trend curve exponent B. Neither are available. As previously discussed, Cochran considered a learning range of 80–95% ($B = 0.32, B = 0.07$) as the most fundamental and long lasting. A learning of 87% ($B = 0.2$) is an approximate midpoint of Cochran's 80–95% range. Not infrequently, 60–80% of a program, product, or process is purchased and 87% learning is a reasonable assumption for this situation. In any case, 1) Wright noted that 88% was appropriate for purchased material,[2] and 2) the Ford Model T had a 16-year history of 86%.[4] Given no additional information the author suggests an assumed learning of 87% ($B = 0.2$) as a reasonable value.

Now that we have the trend curve exponent B, the starter X-Y point is calculated by considering separately or sometimes together WCDD curves and similar improvement curves for the program, product, or process of interest. A Wright curve example follows.

In the region of interest, a point X on the Wright improvement curve abscissa (units) is multiplied by a cost factor, such as ($ R&D/units), to get driver cost, or funding, ($ R&D) for the abscissa of the trend curve ($\$X$). In this manufacturing case, ($ R&D) represents ManTech (Manufacturing Technology) and similar acquisition driver cost program funding.

The corresponding Wright improvement curve ordinate (Y) of cumulative average dollars (cum av $/unit) is multiplied by the X abscissa (units) to get driven cost, ($ acquisition) for the ordinate ($\$Y$) of the trend curve.

Now that a X-Y point is known with the trend curve exponent, the remaining procedure of calculating the proportionality constant A with Eq. (1) is similar to that described above. If the ordinate is a unit improvement curve, for example, the Crawford curve, the ordinate also needs to be multiplied by the cum av/unit factor $[1/(1 - B)]$. The ordinate then becomes cumulative average and, if in dollars (cum av $/unit), can be used as described above.

If not in dollars, for example, Duane's failure rate [(cum av failures/hour) (hours)], the ordinate also needs to be multiplied by a cost factor: e.g., ($ O&S/failures).

Realistic, Reasonable, and Complete Analyses

Of considerable interest to the academician and practitioner alike is that with "no points known" realistic, reasonable, and complete trend and trade "Big 3" analyses of cost elements and subelements separately, or sometimes together, can be performed using the cost-related information available for the WCDD improvement curves. These analyses can consist of multidimensional sets of trend and trade cost relationships, but frequently that is not practical. Considering the realities of the world we live in, there is a paucity of data and estimates needed for high fidelity multidimensional analyses 1) due to less than satisfactory data sources and 2) due to the sensitive proprietary nature of the data and estimates.

The unified approach to funding permits analyses at whatever number of dimensions is practical. If required, one can perform essentially two-dimensional trend and trade analyses by considering an aggregate of driver costs X, funding, and an aggregate of driven costs Y. Even with two-dimensional trend and trade analyses, one still can focus on funding as a cause to effect driven cost and achieve a total cost reduction.

Trend and Trade Relationships

A driver x or aggregate of drivers X, driver cost, causes a change of a driven y or aggregate of drivens Y, driven cost.

Driver cost also causes a change of total t or aggregate of totals T, total cost.

Trend Curve

The trend curve is defined as a cause and effect power function. The power function is a decaying exponential that is used to quantify the relationship of driven cost Y with driver cost X:

$$Y = A(X)^{-B} \tag{1}$$

The relationship of driven cost ratio (Y_2/Y_1) with driver cost ratio (X_2/X_1) is

$$Y_2/Y_1 = (X_2/X_1)^{-B} \tag{2}$$

The relationship of a second driven cost Y_2 with a first driven cost Y_1 is

$$Y_2 = Y_1(X_2/X_1)^{-B} \tag{3}$$

Trade Curve

The trade curve is defined as the sum of driver cost X and driven cost Y, and, with the trend curve, is the model used to reduce total cost:

$$T = X + Y \tag{4}$$

Using Eqs. (1) and (4), the trade curve relationship of total cost T with driver cost X is

$$T = X + A(X)^{-B} \tag{5}$$

Improvement Curve and Trend Curve Slopes

The slope of the improvement curve is the improvement curve log-slope B. The relationship of the improvement curve log-slope B with the ratio of driven cost Y_2/Y_1 and the ratio of driver cost X_2/X_1 is

$$B = [-\ell n(Y_2/Y_1)/\ell n(X_2/X_1)] \tag{6}$$

A characteristic of the improvement curve log-slope B relationship is that it is not changed by scaler multiplication because the relationship is with the ratio of driven cost Y_2/Y_1 as well as with the ratio of driver cost X_2/X_1. That is, multiplying Y by a constant factor a does not change B. Similarly, multiplying X by the same constant factor a or a different constant factor b also does not change B.

When the ratio of driver cost $X_2/X_1 = 2.0$, the relationship of the improvement curve log-slope B, trend curve exponent, with percent learning L is

$$B = [-\ell n(L/100)/\ell n(2.0)] \tag{7}$$

The slope of the trend curve is the trend curve instantaneous slope, prevailing cost payback C. The negative value of the trend curve instantaneous slope is prevailing cost payback C:

$$C = -\mathrm{d}Y/\mathrm{d}X \tag{8}$$

Funding for Minimum Total Cost

With the trend curve exponent B and a single X-Y point of the trend curve known, driver cost for minimum total cost X_M can be calculated using the minimum cost function:

$$X_M = X[(B)(Y/X)]^{[1/(1+B)]} \tag{9}$$

Funding for Prevailing Cost Payback

With the trend curve exponent B, prevailing cost payback C, and driver cost for minimum total cost X_M known, driver cost for prevailing cost payback X_{PC} can be calculated using the simple prevailing cost payback function:

$$X_{PC} = X_M[1/C]^{[1/(1+B)]} \tag{10}$$

With the trend curve exponent B, prevailing cost payback C, and a single X-Y point on the trend curve known, driver cost for prevailing cost payback X_{PC} can be calculated using the general prevailing cost payback function:

$$X_{PC} = X[(B/C)(Y/X)]^{[1/(1+B)]} \tag{11}$$

Driver Cost and Driven Cost Allocation

The ratio of driver cost to total cost X/T is calculated using the driver cost allocation function:

$$X/T = (B/C)/[1 + (B/C)] \tag{12}$$

The ratio of driven cost to total cost Y/T is calculated using the driven cost allocation function:

$$Y/T = 1/[1 + (B/C)] \tag{13}$$

Unified Approach Simplicity

At first, the unified approach might be hard to understand but once understood is quick and easy to use. Also, as previously discussed, a paucity of needed cost data and estimates is obviated.

The unified approach model is robust. By applying improvement curve cost and cost-related information no longer to only trend but to trend and trade, the simplicity of the unified approach increases, not diminishes, its usefulness. Each relationship is no more than a one line formula. This simplicity allows better consideration of driver, driven, and total cost alternatives for more effective, efficient, and affordable decisions. All of the relationships require no more than a few key strokes on a hand-held calculator.

Some of the relationships can be performed without resorting to imprecise rules of thumb, the need of a calculator or pencil and paper. The relationships also can be and are used to provide crosschecks of more comprehensive but harder to understand cost models, such as large main-frame computer routines.

Simplicity and complexity are terms dependent on perspective. One example of a simple model for a complex system is Newton's third law, action and reaction. Another similar example is the Lanchester warfare model, an operations research and systems engineering model, that the author used as the initial basis of developing the unified approach to funding.

Lanchester Warfare Model Analogy

An analogical discussion of the unified approach from a different perspective—a perspective of force confrontation such as the Lanchester warfare model—provides additional insight regarding the relationship of driver and driven costs.

The Lanchester model is composed of two forces that "interact," i.e., they fight. It has been used with many modifications including the unified approach. A blue quality force is one side (driver cost). A red quantity force is the other side (driven cost). The parity evaluation of this scenario is a delicate balancing act of the two opposing sides: blue and red, qualtiy and quantity, driver cost and driven cost. Trend and trade evaluations and assessments using the unified approach are directly related analytically to this parity scenario, which is represented by a growth/decay model of the form $Y = X^Z$, essentially identical to Wright's cost factor equation of over 50 years ago, $F = N^X$ (Ref. 2). For these general cases, Y as well as F is a driven ratio Y_2/Y_1, X as well as N is a driver ratio X_2/X_1. The exponent Z, as well as X, is a diminishing returns exponent, the trend curve exponent B.[15]

The growth/decay characteristics of this model and the unified approach are fundamental. They are applicable to a wide range of applications where the same units required to trend and trade can be expressed in terms of cost or some other different currency, also capable of being used as a measure of value and a medium of exchange.

Numerical Example

A trend and trade numerical example is used to quantitatively describe the unified approach to funding, driver cost, driven cost, and total cost. The example emphasizes a global LCC utilitarian viewpoint of total cost (Table 1 and Fig. 7). At the same time, the numerics of this example should be considered typical for the more parochial subelement cost analyses of lower level cost drivers, drivens, and totals. Acquisition cost and design-to-cost (DTC) are considered similar for this example. That is, the design-to-unit-production-cost (DTUPC) aspect to DTC was used for this example.

The example considers acquisition and O&S together rather than separately. For this example, 87% learning ($B = 0.2$) was assumed for a combined relationship of acquisition and O&S cost with R&D cost. The trend and trade example presented considers drive cost X as R&D funding. It considers driven cost Y as acquisition and O&S cost. Total cost T is LCC, the sum of R&D funding X with acquisition and O&S cost Y.

For brevity, accuracy of the example is limited. Additional accuracy is possible using numbers with more than 1–2 place accuracy.

Trend Curve Exponent

For this example, with 87% learning assumed, the trend curve exponent B using Eq. (7) is

$$B = [-\ell n(87/100)]/[\ell n(2.0)] = 0.2 \tag{14}$$

Breakeven

For this example, a single X-Y point (0.5,20.0) on the trend curve was assumed; $A = 17.4$ with $B = 0.2$, 87% learning. The breakeven R&D funding for minimum total cost (X_M), using Eq. (9) is

$$X_M = 0.5[(0.2)(20.0/0.5)]^{[1/(1+0.2)]} = 2.8 \tag{15}$$

Driver cost Y_M, the acquisition and O&S cost at minimum total cost, using Eq. (3) is

$$Y_M = 20.0[2.8/0.5]^{-0.2} = 14.2 \tag{16}$$

The total cost T_M, LCC at minimum total cost, using Eq. (4) is

$$T_M = 2.8 + 14.2 = 17.0 \tag{17}$$

Prevailing Cost Payback

The R&D funding X_{PC} for a prevailing cost payback of 2 : 1, ($C = 2.0$), using Eq. (10) is

$$X_{PC} = 2.8[1/2]^{[1/(1+0.2)]} = 1.6 \tag{18}$$

Driver cost Y_{PC}, the acquisition and O&S cost at a prevailing cost payback of 2 : 1, using Eq. (3) is

$$Y_{PC} = 20.0[1.6/0.5]^{-0.2} = 15.8 \tag{19}$$

The total cost T_{PC}, LCC at a prevailing cost payback of 2 : 1, using Eq. (4) is

$$T_{PC} = 1.6 + 15.8 = 17.4 \tag{20}$$

Allocation

Driver cost X/T and driven cost Y/T allocations relative to total cost are presented in bar chart and pie chart formats. Using the last three points of Table 1, the cost allocations presented are at and near the breakeven culmination point: $C = 2.0$, 1.0, and 0.5 (Figs. 8, 9).

At the breakeven culmination point, the cost allocation of R&D funding with LCC X/T using Eq. (12) is

$$X/T = (0.2/1.0)/[1 + (0.2/1.0)] = 0.2 \tag{21}$$

At the breakeven culmination point, the cost allocation of acquisition and O&S cost with LCC (Y/T) using Eq. (13) is

$$Y/T = 1/[1 + (0.2/1.0)] = 0.8 \tag{22}$$

Table 1 Trend and Trade Example

R&D (X)	Acquisition and O&S (Y)	LCC (T)	Prevailing cost payback (C)
0.5	20.0	20.5	8.0
0.9	17.8	18.7	4.0
1.6	15.8	17.4	2.0
2.8	14.2	17.0	1.0
5.0	12.6	17.6	0.5

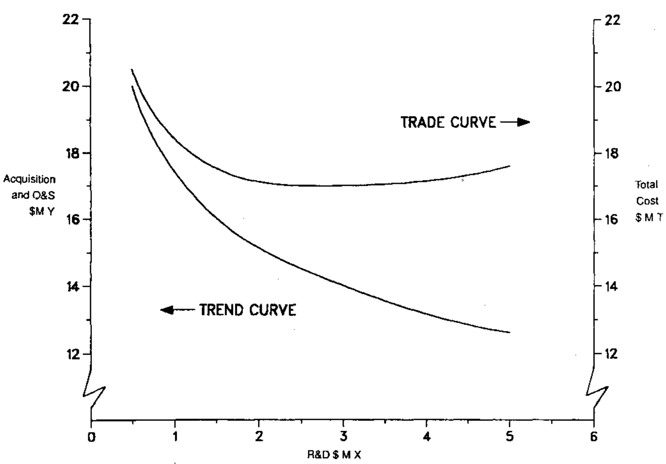

Fig. 7 Example trend curve with trade curve.

Additional Quick and Easy Examples

Sanity checks (SCs) are desirable because they can reveal data and estimate inconsistencies not otherwise acknowledged. During preparation, as well as presentation, SCs particularly are useful to the reviewer, who, while lacking some of the information known by the preparer and presenter, can quantitatively challenge or confirm what is being claimed. The following two numerical examples demonstrate improved means of SCs and should be helpful to preparers and presenters as well as reviewers.

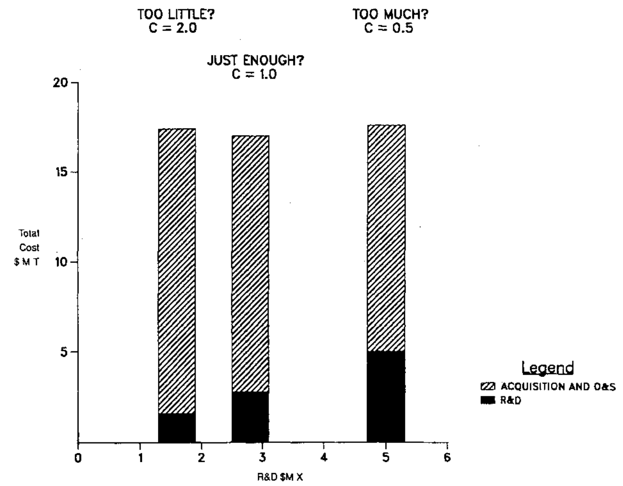

Fig. 8 Driver and driven cost allocations relative to total cost bar chart.

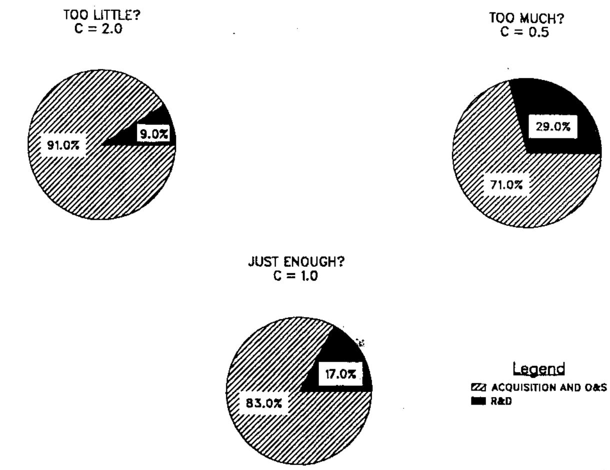

Fig. 9 Driver and driven cost allocations relative to total cost pie chart.

Instantaneous Percent Slope

As previously stated, the trend curve exponent B and the instantaneous percent slope of the improvement curve and the trend curve are the same. This is a useful relationship because the percent sensitivity of driven with driver cost sometimes is known while at the same time percent learning L incorrectly is considered unknown.

Given the model ($Y = AX^{-B}$), the relationship for small changes of percent driven cost ($\%Y$) with percent driver cost ($\%X$) is

$$(\%Y) = -B(\%X) \tag{23}$$

Considering Eq. (23), the relationship of the trend curve exponent B to the ratio of percent driven and driver cost ($\%Y/\%X$) is

$$B = -(\%Y/\%X) \tag{24}$$

Using Eq. (24) for the numerical example given above where a 1.0% driver cost increase causes a 0.2% driven cost decrease, the trend curve exponent B is

$$B = -(-0.2/1.0)$$

$$= 0.2 \tag{25}$$

Using the result of Eq. (25) with Eq. (26), percent learning L is

$$L = 100(2^{-B}) \tag{26}$$

$$= 100(2^{-0.2})$$

$$= 87 \tag{27}$$

Payback, Exponent, and Cost Ratio

Another useful relationship is with the trend curve exponent B, the prevailing cost payback C, and the cost ratio of driven and driver cost (Y/X). Sometimes two of the three are known and the third incorrectly is considered unknown.

The prevailing cost payback C and the cost ratio of driver and driven cost (Y/X) are related. Given the trend curve exponent B, the cost ratio function provides a quick and easy determination of prevailing cost payback:

$$C = B(Y/X) \tag{28}$$

Applying Eq. (28) for a single X-Y point (0.5,20.0) on the trend curve with 87% learning ($B = 0.2$), the prevailing cost payback is

$$C = 0.2(20.0/0.5)$$

$$= 8.0 \tag{29}$$

Discussion

Programs, products, and processes are capable of continual improvement. Learned out flat improvement curves are nonsense. "The improvement curve is an underlying natural characteristic of organized activity, just as the bell-shaped curve is an accurate depiction of normal, random distribution of anything. Improvements are always possible over time, so long as people are encouraged, or even ordered, to seek them."[5]

Executives and the people and resources they manage can continuously improve. Continual improvement is an important fundamental of a Total Quality Management (TQM) culture. The unified approach assists this continual improvement process. The approach offers improved quantitative analyses of driven and total cost with driver cost for more efficient and effective cost allocation and reduction.

Some Funding Nearly Always Cost Effective

While it is possible to encounter a situation where too much or too little funding is being considered or has been applied, a situation where funding per se is counterproductive is unlikely except for extreme rates of learning.

When learning L is at or very near 100%, trend curve exponent B almost zero, an exceptionally large amount of funding is required to achieve even the smallest of cost reductions. For this extreme situation, driven cost tends not to be related to funding. To the extent that funding is unable to drive driven cost, the funding is counterproductive.

The situation is quite similar approaching the opposite extreme of smaller and smaller amounts of learning L, larger and larger values of trend curve exponent B. For this situation, a relatively small amount of funding can achieve almost a complete reduction of driven cost and total cost. Almost no funding is required. Funding beyond the relatively small amount required is counterproductive.

Learning L associated with the relationship of driven cost with driver cost is representative of funding productivity and cost effectiveness. Only at extreme rates of learning might almost any funding be counterproductive. The result is that some funding nearly always is cost effective, provided just enough is applied.

Variable Costs

The unified approach to funding categorizes the composition of total cost in two parts: driver cost and driven cost. The unified approach considers driver cost and driven cost to be variable and considers driven cost related to driver cost.

So-called "fixed" costs are not fixed. Costs are variable. For example, typical "fixed" costs for the financial manager can include leasing, supplies, taxes, and capital expenditures. These "fixed" costs are just as variable as many variable costs. Similarly, a project engineer might consider test hours, technical data item submissions, design life and product specifications as "fixed" cost-related items. Again, these "fixed" costs also are variable.

Collateral Costs

Time is valuable and is a collateral cost that needs to be considered. The value of the Concorde and SR-71 Blackbird and tomorrow's High Speed Civil Transport (HSCT) and National Aero-Space Plane (NASP) is dependent on the collateral cost and benefit of time savings. For example, Wright, in his 1936 paper, noted an "increase in unit cost of 475% for the plane over the car." He also noted "a cruising speed three times that of the car." And he concluded, "only time can prove just how valuable time savings is to mankind."[2]

Other collateral costs, such as product producibility, time of arrival (TOA), initial operational capability (IOC), readiness rate, and fleet effectiveness, should be but sometimes are not included in trend and trade analyses. When collateral costs are not considered, total cost is not captured. Similar to not including all three of the "Big 3" LCC elements, incomplete analyses are performed resulting in deficient and inefficient suboptimizations of cost, Taguchi "worse than a thief" results with best value not achieved. A global LCC utilitarian viewpoint of total cost that includes collateral costs is required.

Percent Cost Sensitivity

The percent cost sensitivity $[(\%Y)/(\%X)]$ is directly related to the trend curve exponent B as shown by Eq. (24), which was presented in a previous section. At and near the breakeven culmination point, total cost T is relatively insensitive to driver cost X. Even with total cost T relatively unchanged at and near the culmination breakeven point, the percent sensitivity of driven cost Y with driver cost X remains the same. For the example presented, a 50% driver cost X increase causes a 10% driven cost Y decrease, $[-(\%Y/\%X) = B = 0.2]$ (Table 1 and Fig. 7).

Money—yours, mine, or ours—is sometimes called the "color of money" and is a concern of nearly everyone, suppliers and customers, project engineers and financial managers. Suppliers tend to emphasize driver cost X because it represents a large share of their funding. Customers tend to emphasize driven cost Y because it represents a large share of their expenses. Project engineers and financial managers have similar emphasis differences.

The uniform percent sensitivity of driven cost Y with driver cost X and the varying sensitivity of total cost T with driver cost X are cause for a lack of a consensus between the business and technical communities of industry and government.

Market, R&D Funding, and Payback

Production quantity and operational usage define a total market level for engines or aircraft. Market level is important because it directly impacts acquisition cost and O&S cost, driven cost Y for the example given. The higher the market level the more R&D funding X required to better allocate and reduce total cost T. Alternatively, at constant R&D funding, the prevailing cost payback increases as the total market level increases.

Business typically prefers calculated paybacks considerably higher than 1 : 1. At the same time, technical not infrequently performs breakeven 1 : 1 design trades ($C = 1.0$). At issue is the projected actual payback to be realized that can be higher or lower than calculated due to many things, not the least of which are production quantity and operational usage, market level.

Risk

Being at the breakeven culmination point ($C = 1.0$) is not at even cost risk. The trade curve is not symmetrical. It is skewed. The slope of the trade curve is steeper before breakeven (Fig. 7). For the same risk exposure considering equal weight for plus and minus uncertainties, a driver cost X might be selected greater than the calculated driver cost for breakeven X_M. Similarly, for the same risk exposure, a driver cost X might be selected greater than the calculated driver cost for a prevailing cost payback X_{PC}.

Now and Later

Higher prevailing cost paybacks C are achieved by funding X now rather than later to incorporate improvements, correct difficulties, and receive benefits as early as possible. Early and substantial R&D funding X frequently is cost effective with high prevailing cost paybacks C. "From the standpoint of total LCC, the optimal level of design effort would be approximately 50% greater than current practice."[16]

For some cost avoidance, containment, and reduction activities, a portion of the funding X can best be done after the R&D phase. For example, Engineering Assistance to Production and Service (EAPS) funding and Component Improvement Program (CIP) funding are cost effective. Even with manufacturing costs and operating and support costs addressed as an integral part of the R&D phase, changing markets, capabilities, and requirements offer substantial cost saving opportunities after the R&D phase and during the acquisition and O&S life cycle phases. Whether funding X is now or later, funding flexibility, the authority to transfer funds to wherever they can do more, needs to be continually improved.

No Free Lunch

Something for something is the real world. There is no free lunch. It takes dollars to save dollars. Spend better to save better is needed. Driver cost X can reduce driven cost Y and total cost T. What is required is "just enough" funding X properly applied where it can do more (Fig. 10).

Future Topics

Follow-on study of the unified approach is suggested in at least two areas: inverse curves and learning improvement.

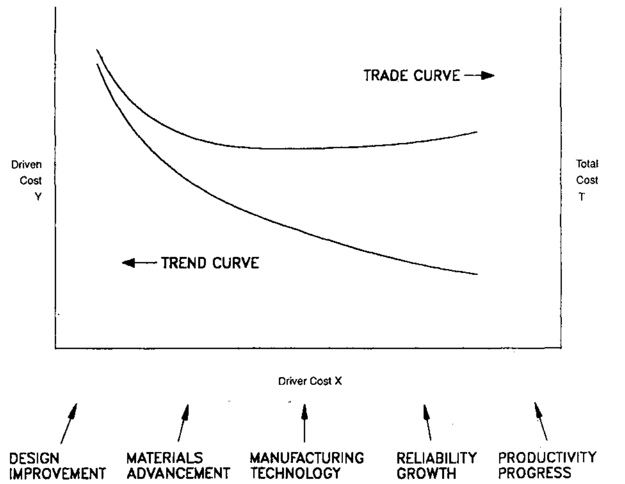

Fig. 10 Takes \$ to save \$.

Inverse Curves

The unified approach and its relationships were described using a decreasing trend curve. Some curves, like Doll's, are increasing (Fig. 4). A unified approach can be applied to increasing curves, inverse trend curves. Provided the instantaneous slope of the inverse trend curve is continuously decreasing and represents diminishing returns, the inverse trend curve relationships are the same or similar to those presented, Eqs. (1–13).

Learning Improvements

With a learning improvement and cost reduction not applied across the board, a scale down of driven and total cost, and sometimes driver cost too, is possible while maintaining or perhaps increasing capability. With learning unchanged and a percent cost reduction applied across the board to driver, driven, and total cost, a "Gramm-Rudman" cost reduction, a scale down of total system capability is likely though probably not wanted.

For example, with a "starter" X-Y point of (0.5,20.0) and 87.0% learning ($B = 0.2$), at breakeven

$$X_M = 2.8$$

$$Y_M = 14.2$$

$$T_M = 17.0$$

With the same "starter" X-Y point of (0.5,20.0) and 70.7% learning ($B = 0.5$), at breakeven

$$X_M = 3.7$$

$$Y_M = 7.4$$

$$T_M = 11.1$$

That is, with capability the same or better at breakeven, a learning improvement from 87.0 to 70.7% can achieve nearly a 50% cost reduction of driven cost and about a 35% cost reduction of total cost while at the same time having, and also needing, over a 30% driver cost increase.

With the same "starter" X-Y point of (0.5,20.0) and 50.0% learning ($B = 1.0$), at breakeven

$$X_M = 3.2$$

$$Y_M = 3.2$$

$$T_M = 6.4$$

At 50% learning and breakeven ($B = 1.0$, $C = 1.0$), driver and driven costs are equal. This result agrees with Eqs. (12) and (13) presented in a previous section. A learning improvement from 70.7 to 50.0% achieves additional cost reductions of more than 55% of driven cost and more than 40% total cost while at the same time having almost a 15% driver cost reduction.

Conclusions

Improvement curve source material has substantive differences in terminology, convention, and nomenclature. Similar differences are noted in technical and financial source material. The development and presentation of the unified approach were hindered by these differences. The unified approach does require some tolerance to and understanding of these differences. The unified approach requires model calibration similar to the improvement curve approaches of Wright, Crawford, Duane, and Doll.

In a world with limited resources, opportunities for continued improvement still are unlimited. Continued improvement is a characteristic of organized activity. The improvement curve, trend curve, itself is no exception. For example, improvement curve use has increased, improved, for over half a century. With the unified approach, the improvement curve now can be used to trend and trade.

"Gramm-Rudman" across-the-board cost reductions can be inappropriate and counterproductive because improvement curve relationships, including the funding relationships of the unified approach, are nonlinear. In a relatively mature constant market, some erosion of business base frequently occurs and is generally recognized to be due to continual improvement reducing driver, driven, and total cost. To better assure long-term survival, continual improvement requires additional improvement, such as successful new ventures that obviate $ business base erosion and can elevate the overall $ business base to ever higher levels.

The unified approach offers a needed "New Math for Productivity."[17] Applying the unified approach to allocate and reduce cost, we all can get started together better and on the right track earlier to achieve and maintain needed excellence for our economic well-being as well as for our defense posture.

Recommendations

Use of the unified approach should not be limited to aerospace. The unified approach has general applicability to industry and government.

Necessary dialogue between industry and government should be increased to more fully realize the benefits of using the unified approach to allocate driver cost and reduce driven and total cost.

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