Modeling Cost Improvement With SEER-H

How SEER-H Handles Learning Curves

Introduction

For many years, analysts have been collecting information on the cost of producing hardware. Over time, it has been shown that unit costs of a product typically decrease as the total production quantity increases. The study of this effect has led to numerous models and theories to predict the cost of product over time for a production program. Often these algorithms fall into a general category of Learning Curve analysis. Once thought to model the increased learning in the hands-on personnel, Learning Curve analysis is now used to envelope cost improvements due to many facets of a continuing production program.

Learning Curve analysis is now regarded as the catch all for cost improvements due to employee learning, design maturation, process maturation, and improved management and planning. As these many factors are often accumulated into one learning cost factor, the analyst is now tasked to evaluate many features of the design and production program before solidifying the cost improvement predictions appropriate for future programs. This paper will:

- Provide an overview of common learning curve theories,
- Discuss some implications of learning curve assumption, and
- Explain approaches to estimating learning with SEER-H

Theory Facet	Wright Cumulative Average	Crawford Unit
Starting Point	Theoretical First Unit - T_1	Theoretical First Unit - T_1
Cost Reduction With Increased Production	Cumulative Average cost decreases as a function of quantity. The Average cost of an item will drop a prescribed percent for every doubling of cumulative units	Unit cost decreases as a function of quantity. The Unit cost of an item will drop a prescribed percent for every doubling of cumulative units
Ending Point	Cost reduction continues forever. Reduction per unit drops considerably past 100th unit.	Cost reduction continues forever. Reduction per unit drops considerably past 100th unit.
Variables	N = Unit Quantity M = Prior Units T_1 = Theoretical First Unit $ S = Learning Curve Slope b = Learning Curve Exponent U_N = Unit Cost of Unit N C_{M-N}= Avg$ Units M+1 to N T_{M-N}= Total Cumulative Cost	N = Unit Quantity M = Prior Units T_1 = Theoretical First Unit $ S = Learning Curve Slope b = Learning Curve Exponent U_N =Unit Cost of Unit N C_{M-N}= Avg$ Units M+1 to N T_{M-N} = Total Cumulative Cost
Learning Curve Exponent	b = Ln(S)/Ln(2)	b = Ln(S)/Ln(2)
Unit Cost	$U_N = T_1 * [N^{(1+b)} - (N-1)^{(1+b)}]$	$U_N = T_1 * N^b$
Cumulative Average Cost	$C_{M-N} = T1 * [N^{(1+b)} - M^{(1+b)}] / (N-M)$	$C_{M-N} = [T_1 /(1+b)] * [(N+0.5)^{(1+b)} - (M+0.5)^{(1+b)}] / (N-M)$
Total Cumulative Cost	$T_{M-N} = T1 * [N^{(1+b)} - M^{(1+b)}]$	$T_{M-N} = [T_1 /(1+b)] * [(N+0.5)^{(1+b)} - (M+0.5)^{(1+b)}]$

Table 1. Two Common Learning Curve Theories are Contrasted

Learning Curve Theory

Numerous mathematical models have be devised to capture cost improvement over the course of a production program. Large data bases have been developed to test these theories for a variety of products and types of production programs. The more common theories tend to agree that the cost of production decreases over the production quality. They tend to differ on the shape of the curve this decrease will follow and for how long production cost should decrease (achievement of steady state). The two most widely recognized learning curve theories are the Wright Cumulative Average Theory (CumAvg) and the Crawford Unit Theory (Unit). Table 1 discusses some of the similarities and differences in these models.

Solution of the formulas documented in Table 1 will always produce lower values for the Crawford Unit Theory than for the Wright Cumulative Average Theory. After the first few units, the cost reduction per unit is approximately the same. Figure 1 illustrates the three cost equations plotted for each theory as a function of the number of units. The three equations illustrated are 1) Total Cumulative Cost, 2) Average Cumulative Cost, and 3) Unit Cost.

The graphs of the Crawford Unit Cost Theory are always below the equivalent graphs of the Wright Cumulative Average Theory. Note that the Crawford Unit plot of Unit Cost is equal to the Wright Cumulative Average Cost plot. Although variations in the two theories are apparent, after the first 10 units, the variation in costs drops considerably.

The information in Table 1 and Figure 1 provide an overview of two prominent learning curve theories. Numerous texts and technical papers have been written on the theory and application of learning curves. If more information is needed on these theories, your Galorath technical support staff may be able to provide you with additional resources.

Implications of Learning Curve Assumptions

As mentioned previously, many program features should be evaluated in terms of their impact on learning and overall cost improvement. Program features may play either a positive or negative impact on cost over time. Both impacts should be evaluated and the resultant cost reduction (hopefully) should be computed. Table 2 describes the type of program aspects which should be evaluated in this context.

In general, to realize cost improvement, one must be able to go from a less efficient, streamlined operation to a more efficient streamlined operation. This then requires a few points to be noted:

- If an efficient steady state is assumed for a program, and much learning is assumed to be taking place, the early units must not have had that same efficiency. This translates into a high first unit cost, a steep rate of learning and a lower steady state cost.
- If an efficient steady state is assumed for a program, and not much learning is assumed to be taking place, the early units must have had that same efficiency. This translates into a low first unit cost, a shallow to non-existent rate of learning and a lower steady state cost.

If an inefficient steady state and inefficient early unit production is assumed for a program, no learning is taking place. This translates into a high first unit cost, a shallow or non-existent rate of learning and a high steady state cost.

A highly automated program tends to posses many of the features listed in the "Favorable Influences" column of Table 2. This translates into a low first unit cost, a shallow or non-existent rate of learning and a low steady state cost.

These points have been summarized in Table 3. The following section describes how to model the various features of these points with SEER-H.

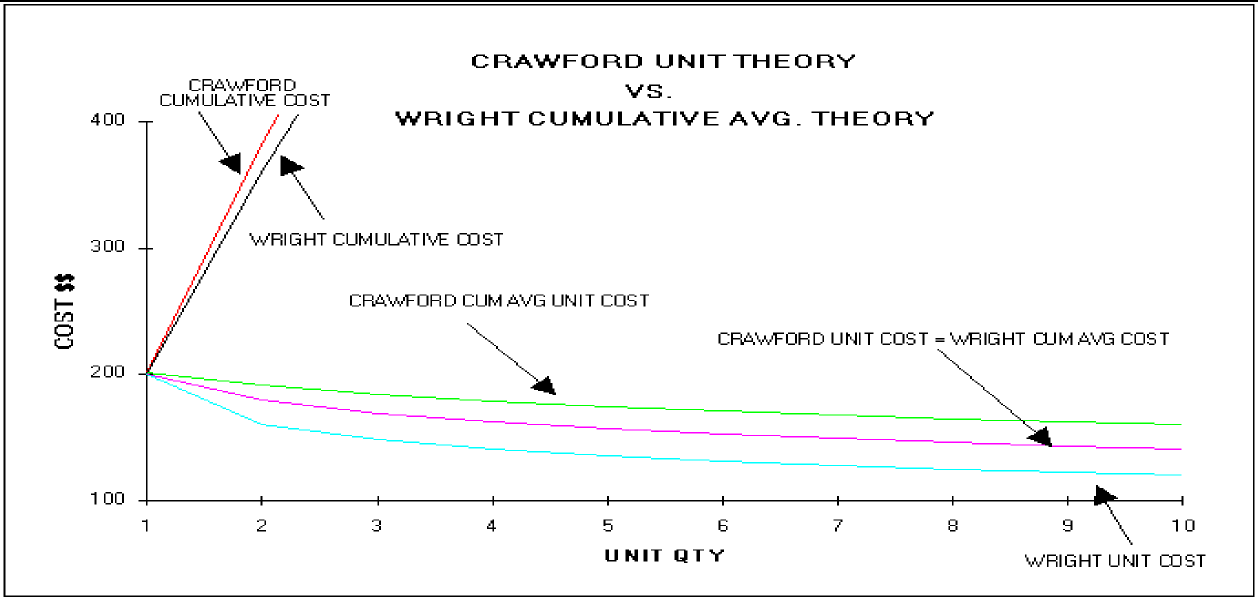

Figure 1. The Crawford Unit Leaning Curve Theory is Contrasted with the Wright Unit Learning Curve Theory in the calculation of Total Cumulative Cost, Cumulative Average Unit Cost and Unit Cost

Favorable Conditions	Program Feature	Unfavorable Conditions
Simple Features Proven Technology Standardized Design	**Product Design**	Complex Features Tech Not Well Understood Many Design Options
Design Set Early Design Documented Well No Outside Impacts on Design	**Design Volatility**	Volatile Design Intra-System Impacts Common Linked w/ External Volatility
Design Well Understood Previous Exp w/ Design Previous Exp w/ Technology	**Design Maturity**	Design New to Production No Experience in Test No Experience in Tech
Simple Steps Easily Verified Same Processes for Each Unit	**Production Process**	Complex Steps Difficult Verification of Test Varied Processes Each Unit
Flat or Gradual Rate Chg No Gaps in Production Available Mat'ls & Supplies	**Production Schedule**	Volatile Production Rate Significant Production Gaps Shortages of Mat'l, Supplies
Skilled People Consistent Work Force Streamlining Work Force	**Production People**	Unskilled Labor Changing Work Force Fixed Head Count
Efficient Tools, Setups Adequate Capacity No Tool & Planning Malfunctions	**Production Tools**	Inefficient tools, setups Inadequate Capacity Tool & Planning Malfunction

Table 2. All aspects of a production program should be evaluated in terms of favorable and unfavorable influences on program cost Over Time

Early Program	Steady State Program	First Unit Cost	Learning Curve %	Steady State
Inefficient	Efficient	High	Steep	Low
Efficient	Efficient	Low	Shallow	Low
Inefficient	Inefficient	High	Shallow	High
Automated - Efficient	Automated - Efficient	Low	Shallow	Low

Table 3. Modeling program learning must compensate for changes in production

SEER-H Learning Curve Application

SEER-H is a hardware acquisition cost estimation model. It estimates cost based on a description of the technical features, intended mission and program characteristics of the item. A general description of the SEER-H model and estimation methodology can be obtained from other SEER-H Technical Notes. This Technical Note is intended to discuss the aspects of the SEER-H estimation methodology applicable to modeling program learning.

Many of the SEER-H input parameters should be reviewed in order to properly model program learning. A tendency exists to alter just the learning curve percentage input. As discussed in the previous section, this independent action is rarely illustrating the real situation. Following are discussions of the learning curve methodology within SEER-H, important parameters to consider when determining learning curve percent, and several case studies illustrating these considerations.

SEER-H Learning Curve Methodology

SEER-H employs two techniques in generating a hardware cost estimate. First, the element's technical description is used to generate an analogy estimate for a like system given a certain set of groundrules. Then parametric cost estimating relationships (CERs) are used to adjust this normalized analogy estimate to the groundrules of the element's mission and program characteristics. Upon completion of these two steps, SEER-H has computed the average unit cost for 100 units of the element. SEER-H data and CERs have been based on lots of production wherever possible because lot production data provides a far more accurate basis for equation derivation than using a given unit (i.e., first unit cost).

SEER-H generates an accurate estimate of average unit cost, and then adjusts the estimate based on the user defined learning assumptions. The user inputs for learning curve percentage and production program profile are used to generate an appropriate first unit cost and cost of all units in the user defined production schedule. Following the ideas outlined in the previous section, these user defined learning assumptions are not described by a single input. Many of the inputs are used to determine the correct steady state estimate and the user input learning curve then calculates the change in cost throughout the production period. Any quantity of units and prior units may be modeled with SEER-H. One should take care to model changes in a steady state situation along with modeling changes in learning assumption. The following sections isolate the SEER-H parameters which affect the steady state and early year estimates.

SEER-H Parameters Affecting Learning Analysis

SEER-H is designed to provide the estimator with flexibility in modeling a variety of design and production scenarios. All issues of modeling program learning can be accounted for with individual SEER-H parameters. Table 4 lists the SEER-H parameters which should be reviewed for such an analysis. The table contains some guidance for parameter settings which correspond to the situation where learning can occur. This translates into a steeper learning curve slope input (i.e., lower percentage). Examples of these types of settings follow in the next few sections.

SEER-H Learning Curves for Typical Aerospace Applications

Many aerospace companies and consortiums have collected production cost data and determined the appropriate learning curve for different types of products built in various production environments. Most systems fall into the complex to very complex category, often pioneering system design and technology features. Many of the systems are built in small quantities and often at variable production rates per year. Another feature of many of these systems is the customer involvement in the product design and production. Continual direction and possibly redirection from the customer is common with changing missions and defense priorities.

These and many additional characteristics can be modeled with the SEER-H hardware estimation model. Table 5 lists some recommended combinations of learning curve setting and other parameter ratings which apply to the situations described above. Based on these situations, the parameter settings which appear reasonable for a range of learning curve percentages are listed. Note that the selection of appropriate learning curve percentage actually follows analysis of these other program features. If the learning curve is known, care should be taken to accurately rate the other parameters to reflect the environment and procedures which were in existence when the learning curve was derived.

SEER-H Learning Curves for Highly Automated Production

Most of the contributions to production cost improvement occur because humans have improved a process. Humans can continually improve an automated process, but the contribution to cost improvement is typically much less than improvements to a manual process would contribute. The basic premise to the learning curve assumption is achieving efficiency through changes in process, people and tools. If the operation is highly automated and very efficient at the start of the program, there is far less cost improvement to be achieved. The program begins at a cost effective point. Unless continual process changes occur, machines do not typically improve upon their own actions over time. Machines also do not typically require the level of management and support human labor requires, again lessening an area for cost improvement.

If the above scenario is in place, the learning curve percentage appropriate for automated production is typically much shallower than that of labor intensive operations. At the high end, 100% learning indicates that the process is in place at the start of the program and will not change over time. Nominally rated at 96% are processes which are highly automated but still require some human interaction or will experience some changes over time. At the lower end, 92% learning indicates an even higher level of human interaction, either as part of the steady state process or because of changes introduced to the process over time. Table 6 illustrates a range of learning curve inputs that may be applicable to an automated production process. The proposed production units should be reviewed for each of these scenarios, as full automation becomes economically viable only with very high rates of production. Again, using all the SEER-H parameters applicable, program learning can be modeled accurately for any automation scenario.

SEER-H Parameter Category	For Increased Learning Potential…	Consider…
Product Description	Complex assemblies, tight tolerances. Electronics with high component densities.	Higher complexity tends to create less learning capacity if the process is manual.
Mission Description	Complexity High, Fault Tolerance High	Operating Environment and Hardware Function affect Product Complexity. Fault Tolerance may aid in achieving efficient test.
New Design	Higher New Design	More New Design introduces inefficiency in the early phases of the program.
Redundant Design	Depends on Design	Redundant Design may coincidentally cause complexity and provide production efficiency.
Certification Level	Very High or Very Low Certification	Higher Certification Levels can increase labor requirements, but also prepare production for the design characteristics.
Integration Level	High Integration if Manual	Higher Integration Level will provide opportunity for learning unless automated.
Developer Capability	Low Developer Capability	Lower Development Capability indicates the potential for design changes in early units.
Development Tools	Low Development Tools	If inconsistent design configuration management existed, potential for learning is higher.
Requirements Volatility	Higher Requirements Volatility	Higher Requirements Volatility will hamper the transition to production. If the steady state assumes efficiency, High Requirements Volatility indicates high potential for learning.
Production Experience	Lower Production Experience	Lower Production Experience indicates potential for learning more per unit.
Production Tools	Lower Production Tools	Lower Production Tools provides more opportunity for improvement over time.
Prototype Quantity	Lower Number or No Prototypes	Low number of Prototypes shifts the required learning experiences over to production.
Prior Units	Lower Number or No Prior Units	Prior units will experience the learning before the current production run.
Production Units	Steady State, Higher Rates	More units built consistently have more potential for realization of learning.

Table 4. Several SEER-H Parameters are used in evaluation of potential program cost improvement over time (i.e.,

SEER-H Parameter Category	Learning Curve 95%	Learning Curve 90%	Learning Curve 85%
Product Description	Mapping Factor 6 to 8	Mapping Factor 4 to 6	Mapping Factor Below 5
Mission Description	Fault Tolerance Low	Fault Tolerance Higher	Fault Tolerance High
New Design	Proven Design Features	Nominal New Design	High New Design Required
Redundant Design	Depends on Design Complexity	Depends on Design Complexity	Depends on Design Complexity
Certification Level	Volatile Certification Requirements	Semi-Volitile Certification Level	Certification Accomplished Well
Integration Level	Integration Low or Automated	Nominal Integration Level	Higher Integration Level if Manual
Developer Capability	Higher Capability if no Design Changes	Nominal Capability with Some Changes	Lower Capability w/ Design Changes
Development Tools	Tight Configuration Control	Some Configuration Control	Low Configuration Control
Requirements Volatility	Low Requirements Volatility	Nominal Volatility of Requirements	Higher Volatility of Requirements
Production Experience	Higher Production Experience	Nominal Production Experience	Lower Production Experience
Production Tools	Good Tools in Place at Start of Program	Some Tools in Place at Start of Program	No Tools in Place at Start of Program
Prototype Quantity	Many Prototypes, > 10	Some Prototypes, > 5	Few or Zero Prototypes, < 5
Prior Units	Many Prior Units Credited to Program	Some or Few Prior Units Credited	No Prior Units Credited to Program
Production Units	Few Production Units w/ Fluctuating Rate	Higher Production Qty w/ Steady Rate	Large Production Quantity w/ Set Rate

Table 5. Several SEER-H parameters are analyzed for impact on resultant learning curves appropriate for typical aerospace programs

SEER-H Parameter Category	Learning Curve 100%	Learning Curve 96%	Learning Curve 92%
Product Description	Less Complex, All Processes Automated	Complex, Most Processes Automated	Very Complex, Difficult to Verify
Mission Description	Fault Tolerance Very High	Fault Tolerance High to Very High	Fault Tolerance Nominal to High
New Design	Design, Technology Well Understood	New Issues in Dsgn & Technology	Design, Technology Not Well Understood
Redundant Design	Simple Design for Redundancy	Complex Design for Redundancy	Difficult Processes due to Redundancy
Certification Level	Minimal Paper Trail - Batch Testing	Some Paper Trail - Automated Test	Some Paper & Labor Required for Test
Integration Level	Little or Automated Integration & Test	Nominal but Auto Integration & Test	Some Manual Integration or Test
Developer Capability	Higher Capability, Low Change Traffic	High Capability, Low Change Traffic	Lower Capability, Moderate Changes
Development Tools	Tight Configuration Control	Some Configuration Control	Low Configuration Control
Requirements Volatility	Low Requirements Volatility	Nominal Volatility of Requirements	Higher Volatility of Requirements
Production Experience	Higher Production Experience	Nominal Production Experience	Lower Production Experience
Production Tools	Good Tools in Place at Start of Program	Some Tools in Place at Start of Program	No Tools in Place at Start of Program
Prototype Quantity	Many Prototypes, > 10	Some Prototypes, > 5	Few or Zero Prototypes, < 5
Prior Units	Many Prior Units Credited to Program	Some or Few Prior Units Credited	No Prior Units Credited to Program
Production Units	Enough Units to Dedicate Processes	Partial Dedication of Production Tools	Lower Units, Sharing Production Resources

Table 6. Several SEER-H parameters are analyzed for impact on resultant learning curves appropriate for

SEER-H Learning Curves for Commercial Application

Commercial product production varies considerably from typical aerospace production programs. Product complexity can range from the very simple to the very complex. Although the product market provides information on desired product characteristics, the customer is rarely involved in the day to day activities of product design and production. In order to make a profit, commercial enterprises either build very expensive items (i.e., high complexity, lower production units) or many less expensive items (i.e., lower complexity, higher production units). Some industries are still highly regulated throughout production and test of their products, but for many commercial enterprises, customer regulation is not an issue.

Each of these extremes can be estimated accurately with SEER-H. The parameters discussed in the previous three sections are again reviewed for logical settings for the commercial product. Table 7 lists the SEER-H parameter rating applicable to a commercial endeavor. Note that many of the parameters may show a larger range of possible values than documented in the previous tables. Table 7 documents a case using a nominal amount of production automation. Table 6 and 7 can be combined to show the different possibilities for commercial production.

Conclusion

The SEER-H hardware estimation model estimates the cost of product acquisition. The concept of learning or cost improvement occurring throughout production of that product involves more than the mere rating of a learning curve percent. Many features of the development and production program must be evaluated prior to determination of expected production learning or cost improvement. SEER-H was designed with just this type of analysis in mind. SEER-H provides the appropriate parameters to rate the important aspects of design and production which affect the assessment of cost improvement throughout production. Several cases were presented on the rating of these parameters, given certain program characteristics. If there are other program aspects affecting your analysis, give SEER Technologies Technical Support a call for ideas.

SEER-H Parameter Category	Learning Curve 95%	Learning Curve 92%	Learning Curve 87%
Product Description	Less Complex, Processes Automated	Complex, Some Processes Automated	Very Complex, Difficult to Verify
Mission Description	Fault Tolerance Very High	Fault Tolerance High	Fault Tolerance Nominal
New Design	Design, Technology Well Understood	Some New Issues w/ Design, Technology	Design, Technology Not Well Understood
Redundant Design	Simple Design for Redundancy	Complex Design for Redundancy	Difficult Processes due to Redundancy
Certification Level	Minimal Paper Trail - Batch Testing	Some Paper Trail - Automated Test	Much Paper & Labor Required for Test
Integration Level	Little or Automated Integration & Test	Nominal Integration & Test	Varied Manual Integration or Test
Developer Capability	Higher Capability, Low Change Traffic	High Capability, Low Change Traffic	Lower Capability, Moderate Changes
Development Tools	Tight Configuration Control	Some Configuration Control	Low Configuration Control
Requirements Volatility	Low Requirements Volatility	Nominal Volatility of Requirements	Higher Volatility of Requirements
Production Experience	Higher Production Experience	Nominal Production Experience	Lower Production Experience
Production Tools	Good Tools in Place at Start of Program	Some Tools in Place at Start of Program	No Tools in Place at Start of Program
Prototype Quantity	Many Prototypes, > 40	Some Prototypes, > 10	Few or Zero Prototypes, < 10
Prior Units	Many Prior Units Credited to Program	Some or Few Prior Units Credited	No Prior Units Credited to Program
Production Units	Enough Units to Dedicate Processes	Partial Dedication of Production Tools	Lower Units, Sharing Production Resources

Table 7. Several SEER-H parameters are analyzed for impact on resultant learning curves appropriate for commercial Production Programs