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A Life Cycle Cost Economics Model for Automation Projects with Uniformly Varying Operating Costs

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A LIFE CYCLE COST ECONOMICS MODEL FOR AUTOMATION PROJECTS WITH UNIFORMLY VARYING OPERATING COSTS*

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ABSTRACT

A mathematical model is developed for calculating the life cycle costs for a project where the operating costs increase or decrease in a linear manner with time. The life cycle cost is shown to be a function of the (1) investment costs, (2) initial operating costs, (3) operating cost gradient, (4) project life time, (5) interest rate for capital, and (6) salvage value. The results show that the life cycle cost for a project can be grossly underestimated (or overestimated) if the operating costs increase (or decrease) uniformly over time rather than being constant as is often assumed in project economic evaluations. The following range of variables is examined: (1) project life from 2 to 30 years, (2) interest rate from 0 to 15% per year, and (3) operating cost gradient from 5-90% of the initial operating cost. A numerical example plus graphs is given to help the reader calculate project life cycle costs over a wide range of variables.

I. INTRODUCTION

There has been a continuous effort over the last ten years to automate the Deep Space Network (DSN). The DSN was established by the National Aeronautics and Space Administration (NASA) under the management of the Jet Propulsion Laboratory at Caltech. The DSN is designed for two-way communications with unmanned spacecraft traveling about 16,000 km (10,000 miles) from Earth to the farthest planets of our solar system. DSN antennas are located in California, Australia, and Spain to support planetary, and interplanetary flights.

As an example of past automation efforts, the crew size of the Deep Space Station No. 12 at Goldstone, California has decreased from 15 people in 1967 to 4 in 1975. Further automation requires large capital investments that must be justified on an economic basis.

In the last few years, there has been a strong emphasis on DSN cost effectiveness. Cost effectiveness is defined as end users station hours per dollars of funding. Funding can be divided into two areas:

1. Investment costs for new projects, and

2. Operations and maintenance costs over the life of the project. For brevity, operations and maintenance costs (O&M) will be called operating costs in this paper. Future operating costs for a project are often more difficult to estimate than the initial project investment cost.

With relatively constant budgets and the growth in annual operating costs, there have been less funds available for new project implementations and this makes it harder to justify further DSN automation projects. This same phenomenon is occurring in other government installations. For example, the Air Force Systems Command[1] has seen operating costs grow from 45% of their budget in 1962 to 60% in 1975. At the same time, new project investments dropped from 55% of their budget in 1962 to 40% in 1975. This situation is depicted qualitatively in Fig. 1.

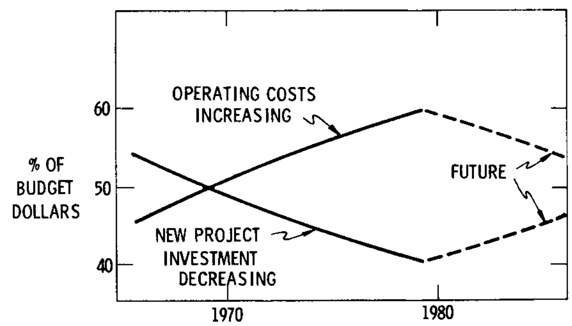

Fig. 1 Dollar allocation between new project investments and operating costs

How did this situation arise where operating costs are continually consuming a larger share of the budget? There are two major reasons:

1. Budget growth rates have been below inflation rates, and

2. Past economic methodologies used for project evaluation accentuated the problem by trying to minimize initial investment at the expense of future operating costs.

For example, one of the most popular economic methodologies in the defense industry selects a project based on initial cost criteria without considering the implications of future operating costs over the life of the project. However, in many cases, the initial acquisition cost is less than the ownership costs, such as the cost of materials and labor to operate and maintain the system.

A relatively new economic methodology called life cycle costing (LCC) attempts to overcome these difficulties. This method incorporates into the project evaluation procedure not only the initial project costs but also the total operating costs over the project life cycle. Hopefully, the use of life cycle costing concepts will improve the budget balance between operating costs and investments as shown by the dashed lines in Fig. 1. The purpose of this paper is twofold. The first goal is to propose a life cycle cost model

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for use in evaluating projects that have uniformly increasing or decreasing operating costs during the life of a project. And the second goal is to compare the life cycle operating costs (LCOC) calculated from this model to the LCOC when the operating costs are constant over time as is often assumed in project economic evaluations.

Although our immediate interest is in calculating LCOC for DSN automation projects, the methodology can be applied to any project in a non-profit organization. In addition, the LCC model can easily be expanded to profit oriented companies by adding depreciation and tax terms to the model.

II. ADVANTAGES AND DISADVANTAGES OF LIFE CYCLE COST (LCC) ANALYSIS

Life cycle costs are the initial investment costs plus the total operating costs over the life of the project. One of the major goals of LCC analysis is to minimize the total cost of a project over its life time. There are several advantages and disadvantages of LCC analysis.

A. Advantages

There are three important advantages of LCC calculations. First, LCC analysis is a management tool used to select the best project among several alternatives. Second, LCC analysis is used to evaluate a specific project by doing trade-off studies between initial investment costs and future operating costs in order to minimize total costs during a project's life cycle. There is a third less obvious advantage. The additional analysis required to estimate life cycle operating costs yields insight into reducing initial investment costs and insight into designing equipment to minimize operating costs.

A recent LCC analysis for energy conservation[2] showed a net investment savings of $46,000 in addition to an annual operating cost savings of $4,000. In this case, LCC analysis actually reduced both initial investment and future operating costs; however, this is the exception rather than the rule. Usually LCC analysis results in a trade-off between larger initial investment versus lower future operating costs. In the typical DSN automation project evaluation, there is usually a large capital investment required that needs to be offset by reduced manpower and maintenance costs.

B. Disadvantages

The advantages of LCC are more apparent than the disadvantages. There are two major disadvantages. First, if the estimate for the project life is too long, which often happens because of new technology replacing obsolete technology, then more is probably invested in the original project than is justified. For example, if LCC analysis is used to evaluate a hardware computer project, then the project life must be estimated very carefully because of rapidly changing technology. An arbitrary standard project life, like 10 years which is usually used for LCC in the DSN, can be very misleading for projects that wind up with a shorter life.

A second major problem with LCC is developing a model to describe the operating costs over a project life time. Since the available data bases and predictive tools for estimating operating costs are usually inadequate, LCC is often very difficult, if not impossible, to apply to a real problem. To overcome this obstacle, a simplified model is proposed in this paper.

Many standard reference books on engineering economics[3,4] indicate that operating costs sometimes increase or decrease in a uniform manner with time. The goal of this paper is to introduce a useful methodology to calculate LCC assuming a uniform increase (or decrease) each year in operating costs. This means that the proposed model will incorporate a linearly increasing (or decreasing) function to approximate the unknown operating cost function. In addition, a comparison will be made between using a linear operating cost function versus assuming a constant operating cost function as is often used in project evaluations.

III. DEVELOPMENT OF THE LIFE CYCLE COST (LCC) MODEL

The following discussion of the LCC model is divided into five parts:

1. Propose a model for the LCC of a project with uniformly increasing or decreasing operating costs,
2. Solve the resulting analytical expression,
3. Provide graphs so that others can use the results,
4. Compare the LCOC for a linear operating cost function to a constant operating cost function, and
5. Give an example to illustrate how to use the results.

A. Life Cycle Cost Model

Life cycle costs are defined as the sum of the initial costs, P, plus the sum of the operating costs, U, over the project life, n. Thus,

$$LCC = P + \sum_{j=1}^{n} U_j \tag{1}$$

Let's assume the operating cost function, U, is a uniformly increasing function of time (later we will consider the case where it is a decreasing uniform function of time). For the purposes of this development, we will consider discrete step increases in costs rather than a continuous function because the discrete approach more closely matches most budgeting and forecasting systems.

We will define uniformly increasing operating costs as shown below in Table 1 and as illustrated in Fig. 2. The initial operating cost in year number 1 is designated by U_I^0 and the operating cost increases an amount R each year.

Table 1. Uniformly increasing operating costs

Uniformly increasing operating costs, U_I	Time, years
U_I^0	1
$U_I^0 + R$	2
$U_I^0 + 2R$	3
$U_I^0 + 3R$	4
⋮	⋮
$U_I^0 + (n-2)R$	$n-1$
$U_I^0 + (n-1)R$	n

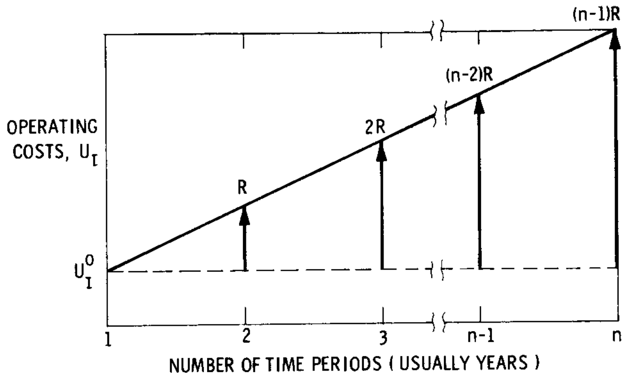

Fig. 2 Uniformly increasing operating costs

We now need to introduce the time value of money for these future operating cost cash flows. The present value, PV, of a future amount of money, F is

$$PV = F(1+i)^{-n} \tag{2}$$

where i is the time value of money (interest rate) per year and n is the number of years between the cash-flows PV and F. The factor $(1+i)^{-n}$ is referred to as the discounting factor and accounts for the time value of capital. For the no discounting case, i is zero.

B. Analytical Solution for the Life Cycle Cost Model

The operating cost term $\sum_{j=1}^{n} U_j$, can be divided into two parts.

$$\sum_{j=1}^{n} U_j = U_c(n,i) + U_I(n,i) \tag{3}$$

The first part, $U_c(n,i)$, represents the operating costs at any interest rate, i, and any project life, n, when the operating costs are constant throughout the project life. The second term, $U_I(n,i)$, represents the additional operating costs for any i and n assuming that operating costs increase in a uniform manner over time.

The present value of $U_c(n,i)$ is given by

$$U_c(n,i) = \frac{U_I^0}{1+i} + \frac{U_I^0}{(1+i)^2} + \cdots + \frac{U_I^0}{(1+i)^{n-1}} + \frac{U_I^0}{(1+i)^n} \tag{4}$$

or

$$U_c(n,i) = U_I^0 \sum_{j=1}^{n} \frac{1}{(1+i)^j} \tag{5}$$

and the present value of $U_I(n,i)$ is given by

$$U_I(n,i) = \frac{R}{(1+i)^2} + \frac{2R}{(1+i)^3} + \cdots + \frac{(n-2)R}{(1+i)^{n-1}} + \frac{(n-1)R}{(1+i)^n} \tag{6}$$

or

$$U_I(n,i) = R \sum_{j=2}^{n} \frac{j-1}{(1+i)^j} \tag{7}$$

It is relatively easy to show that

$$U_c(n,i) = U_I^0 \frac{(1+i)^n - 1}{i(1+i)^n}, \qquad i \neq 0 \tag{8}$$

and

$$U_I(n,i) = R \frac{(1+i)^n - (1+ni)}{i^2(1+i)^n}, \qquad i \neq 0 \tag{9}$$

For the case of i = 0, $U_c(n,0) = nU_I^0$ and $U_I(n,0) = Rn(n-1)/2$.

The LCC for a project with a life of n years and a time value of money, i, is obtained by combining Eqns. (1) and (3) to get

$$LCC = P + U_c(n,i) + U_I(n,i) \tag{10}$$

Now, by substituting Eqns. (8) and (9) into Eqn. (10), we obtain for the total present value of the LCC,

$$LCC = P + U_I^0 \frac{(1+i)^n - 1}{i(1+i)^n} + R \frac{(1+i)^n - (1+ni)}{i^2(1+i)^n} \tag{11}$$

Equation (11) is the general analytical expression for LCC when the operating costs increase uniformly each year during the project life. The expression

$$\frac{(1+i)^n - 1}{i(1+i)^n} \tag{12}$$

is usually called the annuity present worth factor and the expression

$$\frac{(1+i)^n - (1+ni)}{i^2(1+i)^n} \tag{13}$$

is usually called the gradient present worth factor[3].

For the case of uniformly decreasing operating costs, the total LCC for a project is given by Eqn. (11) if we change the positive sign to a negative sign for the R term in the equation. However, the following restriction on R applies in most real cases.

$$R \leq \frac{U_I^0}{n-1}$$

There are two additional things one may want to consider when calculating the total LCC of a project. First, there is the possibility that the project equipment may have a salvage value, and second, the project investment cost may be spread over several years.

A project's facilities may have some residual or salvage value at the end of the project's life. The salvage value, SV, is defined as the net realizable value after any dismantling or removal costs have been deducted from the actual cash value. The salvage value may be either positive or negative. The present value of this cash flow received n years from now with a time value of money, i, is

$$SV(1+i)^{-n} \tag{14}$$

In addition to the salvage value consideration, the project investment cost, P, may be spread over say, k years before startup. The total project investment is

$$P = P_0 + P_{-1} + P_{-2} + P_{-3} + \cdots + P_{-(k-1)}$$

where the subscripts refer to the number of years prior to project startup. We have arbitrarily chosen n = 1 to be the first year of operation. As a result, we must compound these investment costs to calculate the total present value of these individual investments. Thus,

$$P = P_0 + P_{-1}(1+i) + P_{-2}(1+i)^2 + P_{-3}(1+i)^3 + \cdots P_{-(k-1)}(1+i)^{k-1} \quad (15)$$

or

$$P = \sum_{j=0}^{k-1} P_{-j}(1+i)^j \quad (16)$$

Occasionally a project will have investment costs after startup; for this case, the investment cash flows are discounted back to n = 0 just like the treatment of the salvage value. Now if we incorporate the salvage value from Eq. (14) and the project investment costs from Eq. (16) into the LCC cost Eq. (11), we obtain the following general equation for the total present value of the LCC of a project.

$$LCC = \sum_{j=0}^{k-1} P_{-j}(1+i)^j + U_I^0 \frac{(1+i)^n - 1}{i(1+i)^n} + R\frac{(1+i)^n - (1+ni)}{i^2(1+i)^n} - SV(1+i)^{-n} \quad (17)$$

C. Results from the Life Cycle Cost Model

To help calculate LCC for a project, the functions $U_I(n,i)/R$ and $U_c(n,i)/U_I^o$ are summarized in Figures 3 and 4 for i = 0, 0.05, 0.10 and 0.15 and n from 2 to 30 years. The ratio of $[U_I(n,i)/R] / [U_c(n,i)/U_I^o]$ indicates the large difference in LCOC between using a model with a uniform increase in operating costs versus assuming a model where operating costs are constant over time. For example, in the DSN we often use a project life of n = 10 years, and if we assume i = 0.10 like the Department of Defense[5], then $[U_I(n,i)/R] / [U_c(n,i)/U_I^o]$ is 3.7. For most projects, R/U_I^o will be between 0.01 and 0.9. A typical value for R/U_I^o is 0.1, and for this case, the ratio of $U_I(n,i)/U_c(n,i)$ is 0.37. If the project has uniformly increasing operating costs and we had assumed that the operating costs were constant over time, then the operating cost portion of LCC would be off by 37% which is a very significant error in calculating operating costs.

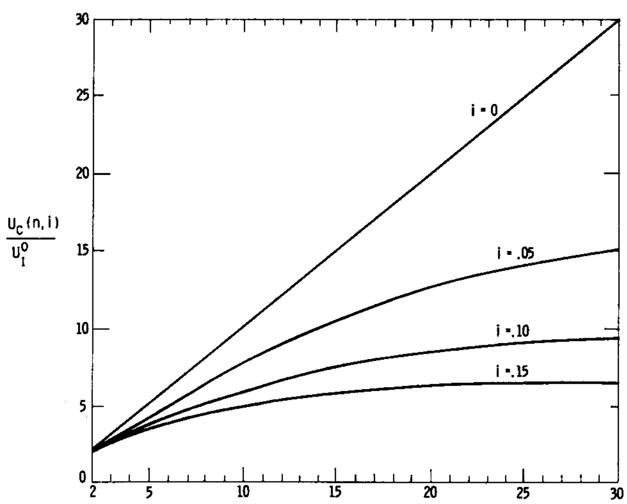

Fig. 3 Uniform operating costs as a function of interest rate and time

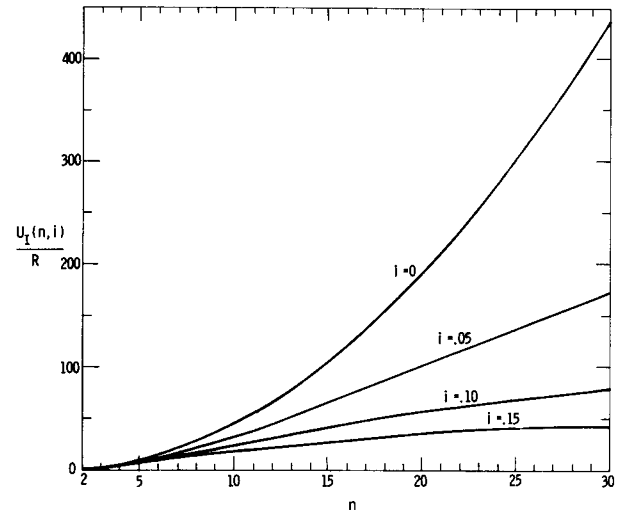

Fig. 4 Uniformly increasing operating costs as a function of interest rate and time

The percent error in calculating operating costs is summarized in Table 2 for the entire range of R/U_I^o from 0.01 to 0.9 for i = 10% and a 10 year life.

Table 2. Ratio of uniformly increasing operating costs to uniform annual operating costs for *i* = 10 percent and *n* = 10 years

R/U_I^0	$\frac{U_I(10, 0.10)}{U_c(10, 0.10)} \times 100\%$
0.01	4
0.05	19
0.1	37
0.3	112
0.5	186
0.7	261
0.9	335

Figure 5 shows the ratio of linearly increasing costs to uniform operating costs for i = 0.10 and n = 2 to 30 years in the range of R/U_I^o from 0.05 to 0.9. This data is shown for i = 0.10 because this is the interest rate most often used by government agencies such as the Department of Defense[5].

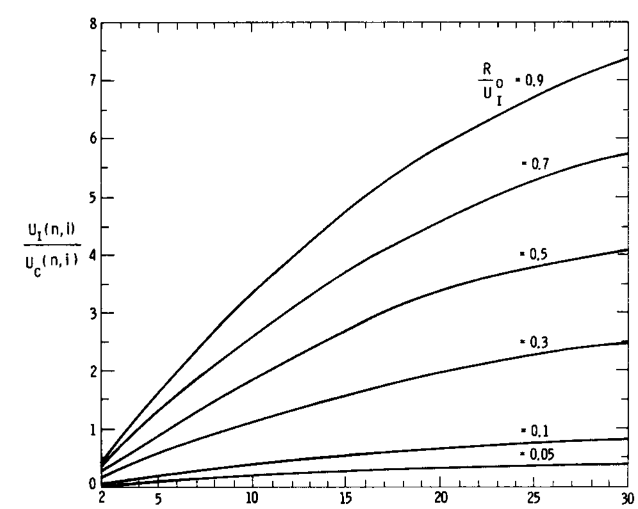

Fig. 5 Ratio of uniformly increasing operating costs to uniform operating costs as a function of time and R/U_I^o at an interest rate of 10%

In Fig. 6 the ratio of $U_I(n,i)/U_c(n,i)$ is shown for a typical value of $R/U_I^O = 0.1$ and an interest rate in the range of 0 to 15% and project life of 2 to 30 years.

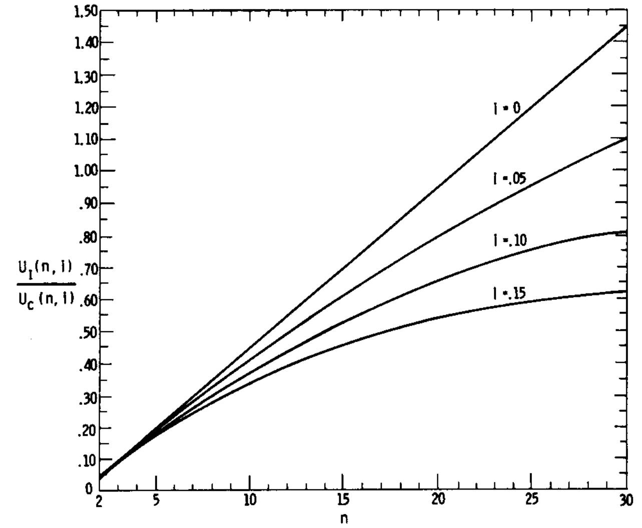

Fig. 6 Ratio of uniformly increasing operating costs to uniform operating costs as a function of time and interest rate for $R/U_I^O = 0.1$

From Figs. 5 and 6, we see that the ratio of $U_I(n,i)/U_c(n,i)$, (1) increases with increasing project life, (2) decreases with increasing interest rate, and (3) increases with increasing R/U_I^O ratio.

D. Life Cycle Cost Example

Here is a simplified example to show how the analytical solution and accompanying figures can be used to calculate the LCC for a project.

1. Problem Statement. We want to calculate the LCC for an automation project that has an initial investment cost of $1,000,000. The forecast for the initial operating cost is $100,000 and these operating costs will increase $10,000 per year. Let's use a project life of 10 years and a cost of capital of 10%. In addition, we will assume the equipment has no salvage value. These six input variable are summarized in Table 3.

2. Problem Solution. The problem can be solved by using Eq. (10) or Figs. 3 through 6. From Eq. (9), $U_I(10,0.1)/R = 22.891$ and from Eq. (8), $U_c(10,0.1)/U_I^O = 6.145$. Therefore, $U_I(10,0.1) = \$228,910$ and $U_c(10.0.1) = \$614,500$. The total LCC for this automation project from Eq. (10) is $1,843,410. Notice that the total LCC for this automation project is almost double the initial investment cost of $1,000,000. Also, notice that if the operating costs were assumed to be constant over the project life rather than increasing a modest $10,000/year, then the LCC would have been underestimated by $228,910. This LCC example solution is summarized in the bottom half of Table 3. Note that the ratio of the increasing operating cost term to the uniform operating cost term is $228,910/ $614,500 = 0.37. This ratio is summarized in Table 2 for i = 0.10 and n = 10 years, and in Fig. 5 for i = 0.10 and n from 2 to 30 years, and in Fig. 6 for $R/U_I^O = 0.1$ and n from 2 to 30 years.

If we modify this example slightly, by increasing R from $10,000 to $15,000 per year, then the LCOC is $1,072,320. The LCOC thus exceeds the initial capital investment of $1,000,000. This is not at all unusual where the LCOC of a project is larger than the original investment cost.

Table 3. LCC example summary

Variable	Symbol	Amount
Input		
Initial investment	P	$1,000,000
Initial operating cost	U_I^0	$100,000
Annual operating cost increase	R	$10,000/year
Time value of money	i	10%
Project life	n	10 years
Salvage value	SV	0
Output		
Increasing operating cost factor	$U_I(n, i)/R$	22.891
Uniform operating cost factor	$U_c(n, i)/U_I^0$	6.145
Increasing operating cost term	$U_I(n, i)$	$228,910
Uniform operating cost term	$U_c(n, i)$	$614,500
Total Life Cycle Cost	LCC	$1,843,410

IV. SUMMARY

1. We have seen that operating costs are continuing to chew up a larger percentage of the total budget for a high technology government agency like the Air Force Systems Command. As operating costs continue to take a larger piece of the budget pie, investment in new projects like automation must be reduced. As new projects to upgrade the system are deferred or eliminated because of lack of budget funds, the present operating system becomes obsolete. The key question is--how can this trend be turned around in an environment with a relatively constant total budget? One potential answer is to introduce a new economic evaluation procedure that will predict the total life cycle cost of a system rather than just the initial investment cost. In the past, many high technology projects have been evaluated on a basis where minimizing the initial project investment was the key optimization variable rather than minimizing the total LCC.

2. LCC evaluation has several advantages and also several disadvantages. The advantages are: (1) to compare alternate projects, (2) to minimize the total project cost over the project life time, and (3) to give insight into reducing initial investment costs as well as insight into designing equipment to reduce operating costs. Before LCC can be calculated, penetrating cost and design questions need to be asked and answered. This process may be as valuable as the LCC methodology itself.

One of the disadvantages of LCC is that the estimate of project life is critical in the economic calculation. If the project life estimate is incorrect, then the wrong project may be selected.

The second major obstacle to using LCC is developing a model to predict the operating costs over a project's life. This disadvantage has kept LCC analysis from being more widely used.

3. In this paper, a simple model was proposed for predicting the operating cost function over time. This model assumed that operating costs increase (or decrease) uniformly over time. The resulting formula for LCC is shown below.

$$LCC = \underbrace{\sum_{j=0}^{k-1} P_{-j}(1+i)^j}_{\text{initial investments}} + \underbrace{U_I^0 \frac{(1+i)^n - 1}{i(1+i)^n}}_{\text{uniform annual operating costs}} \quad (18)$$

$$+ \underbrace{R\frac{(1+i)^n - (1+ni)}{i^2(1+i)^n}}_{\text{uniformly increasing or decreasing operating costs}} - \underbrace{SV(1+i)^{-n}}_{\text{salvage value}}$$

The present value of the LCC is a function of the project life, n, the cost of capital, i, the increase (or decrease) of operating costs per year, R, the salvage value, SV, and the constant operating costs, U_I^0. The results of this model are shown in Figs. 3 through 6 and Table 2. The difference between assuming a constant operating cost function vs. a uniformly increasing (or decreasing) operating cost function becomes more important as the project life increases and the cost of capital decreases. An example was given illustrating how one could apply these results to calculate the LCC for an automation project. In this typical example, the operating costs turned out to be almost half of the total LCC for the project.

Some projects exhibit the so-called bathtub effect where operating costs at first decrease with experience and then level off and finally start to increase as the equipment gets rather old. The model described above could be used to calculate the LCC for this type of project by assuming that initially the operating costs decreased uniformly (-R), then leveled off during the mid life of the project (R = 0), and finally increased uniformly (R) as the project approached the end of its life cycle.

V. FUTURE WORK

A. Operating Cost Function

How the operating cost function varies with time for an automated system or subsystem needs to be examined in more detail by using historical data. Is the operating cost function linear as used in the model herein or is the operating cost function some other simple or complicated function; or is the cost function the same for similar subsystems? These questions need to be tackled and answered before LCC can be applied universally.

B. Probability or Risk Analysis

The future cash flows that are used to calculate the LCC for an automation project have some probability or range associated with them. In other words, these estimates may not be, and in fact, are rarely close to the final outcome. As a result, the calculation of LCC could be improved by superimposing risk or sensitivity analysis on the future cash flows. This might give a more accurate range for the LCC of a project.

C. Learning Curve

The learning curve concept has long been recognized and used in manufacturing industries. It is well known, for example, that the time to perform repetitive operations declines in a negative exponential curve. It seems reasonable to take account of the learning curve in our LCC economic model. Preliminary work is now underway to apply the learning curve to operating cost functions.

VI. REFERENCES

1. Gregory, W. H., "Life Cycle Cost Concept Pushed by AFSC," Aviation Week and Space Technology, McGraw-Hill, July 19, 1976, pp. 22-24.

2. "Life Cycle Costing Is Key to Conservation," Engineering News-Record, McGraw-Hill, November 13, 1975, p. 48.

3. Tarquin, A. J. and Blank, L. T., Engineering Economy, McGraw Hill, 1976.

4. Neuman, D. G., Engineering Economic Analysis, Engineering Press, 1976.

5. Schultz, G. P., "Cost Benefit Factors," U. S. Government, Office of Management and Budget, Circular No. A-94.